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(12) **United States Patent**
Islam

(10) **Patent No.: US 6,603,594 B2**
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(54) **MULTI-STAGE OPTICAL AMPLIFIER AND BROADBAND COMMUNICATION SYSTEM**

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(73) Assignee: **Xtera Communications, Inc.**, Allen, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/007,643**

(22) Filed: **Mar. 19, 2002**

(65) **Prior Publication Data**

US 2003/0058523 A1 Mar. 27, 2003

Related U.S. Application Data

(63) Continuation of application No. 09/471,753, filed on Dec. 23, 1999, now Pat. No. 6,359,725, and a continuation-in-part of application No. 09/471,747, filed on Dec. 23, 1999, now Pat. No. 6,335,820.

(60) Provisional application No. 60/089,426, filed on Jun. 16, 1999.

(51) **Int. Cl.**[7] **H01S 3/00**

(52) **U.S. Cl.** **359/334**

(58) **Field of Search** 359/334

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,616,898 A	10/1986	Hicks, Jr.	350/96.15
4,699,452 A	10/1987	Mollenauer et al.	350/96.16
4,932,739 A	6/1990	Islam	350/96.15
4,995,690 A	2/1991	Islam	350/96.15
5,020,050 A	5/1991	Islam	370/4
5,078,464 A	1/1992	Islam	385/122
5,101,456 A	3/1992	Islam	385/27
5,115,488 A	5/1992	Islam et al.	385/129

(List continued on next page.)

FOREIGN PATENT DOCUMENTS

EP	0 903 877 A2	3/1999	H04B/10/18
EP	1 054 489 A2	11/2000	
EP	1180860 A1 *	2/2002	H04B/10/17
WO	98/42088 A1	9/1998	H04B/10/17
WO	99/66607 A2	12/1999	
WO	WO 99/66607 *	12/1999	
WO	00/49721 A2	8/2000	

OTHER PUBLICATIONS

U.S. application # 60/310,147. "Active Gain Equalizers and Bi–Directional Raman Amplifiers". Islam et al. Filed Aug. 3, 2001.*

(List continued on next page.)

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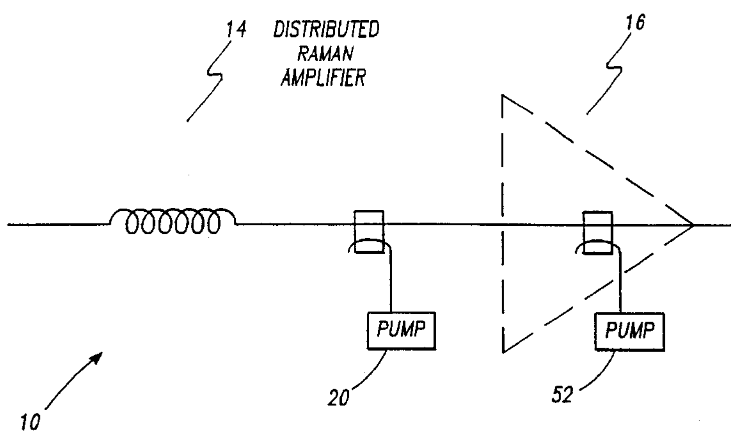
(57) **ABSTRACT**

A multi-stage optical amplifier includes an optical fiber with at least a first Raman amplifier fiber and a second Raman amplifier fiber. The optical fiber is configured to be coupled to at least one signal source that produces at least a signal wavelength λ_s and at least two pump sources that collectively produce a pump beam of wavelength λ_p. Pump wavelength λ_p is less than signal wavelength λ_s. Signal input, signal output and a first pump input port are each coupled to the optical fiber. The first Raman amplifier fiber is positioned between the signal input port and the pump input port. The second Raman amplifier fiber is positioned between the pump input port and signal output port. A second pump input port is coupled to the optical fiber and positioned between the second Raman amplifier fiber and the signal output port. A first lossy member is positioned between the pump input port and the signal output port. The lossy member is lossy in at least one direction so that passage of the pump radiation of wavelength λ_p from the second to the first length of amplifier fiber is substantially blocked. The signal flows in a first direction and the pump beam flows in a reverse direction relative to the first direction.

69 Claims, 20 Drawing Sheets



U.S. PATENT DOCUMENTS

5,224,194 A		6/1993	Islam	385/122
5,369,519 A		11/1994	Islam	359/173
5,485,536 A		1/1996	Islam	385/31
5,559,920 A		9/1996	Chraplyvy et al.	385/123
5,623,508 A		4/1997	Grubb et al.	372/3
5,629,795 A		5/1997	Suzuki et al.	359/337
5,664,036 A		9/1997	Islam	385/31
5,673,280 A		9/1997	Grubb et al.	372/3
5,778,014 A		7/1998	Islam	372/6
5,790,300 A		8/1998	Zediker et al.	359/334
5,796,909 A		8/1998	Islam	385/147
5,815,518 A		9/1998	Reed et al.	372/6
5,861,981 A		1/1999	Jabr	359/341
5,887,093 A	*	3/1999	Hansen et al.	359/160
5,905,838 A		5/1999	Judy et al.	385/123
5,959,750 A		9/1999	Eskildsen et al.	359/134
5,978,130 A		11/1999	Fee et al.	359/341
6,008,933 A		12/1999	Grubb et al.	359/341
6,043,927 A		3/2000	Islam	359/332
6,052,393 A		4/2000	Islam	372/6
6,081,366 A		6/2000	Kidorf et al.	359/341
6,088,152 A		7/2000	Berger et al.	359/334
6,101,024 A		8/2000	Islam et al.	359/334
6,151,160 A		11/2000	Ma et al.	359/341
6,163,636 A		12/2000	Stentz et al.	385/24
6,181,464 B1		1/2001	Kidorf et al.	359/334
6,191,854 B1		2/2001	Grasso et al.	359/124
6,191,877 B1		2/2001	Chraplyvy et al.	359/124
6,219,176 B1		4/2001	Terahara	359/341
6,236,496 B1		5/2001	Yamada et al.	359/341
6,239,902 B1		5/2001	Islam et al.	359/334
6,239,903 B1		5/2001	Islam et al.	359/337
6,263,139 B1	*	7/2001	Kawakami et al.	359/161
6,310,716 B1		10/2001	Evans et al.	359/334
6,335,820 B1		1/2002	Islam	359/334
6,356,383 B1		3/2002	Cornwell, Jr. et al.	359/334
6,356,384 B1		3/2002	Islam	359/334
6,359,725 B1		3/2002	Islam	359/334
6,370,164 B1		4/2002	Islam	372/6
6,374,006 B1		4/2002	Islam et al.	385/15
6,381,391 B1		4/2002	Islam et al.	385/123
6,404,964 B1	*	6/2002	Bhagavatula et al.	372/6
6,414,786 B1	*	7/2002	Foursa	359/334
6,417,959 B1		7/2002	Bolshtyansky et al.	359/334
6,437,906 B1	*	8/2002	Di Pasquale et al.	359/337.2
2002/0001123 A1		1/2002	Miyakawa et al.	359/334

OTHER PUBLICATIONS

Rottwitt et al. "Detailed Analysis of Raman amplifiers for Long–Haul Transmission". OFC '98. 1998. pp. 30–31.*

Rottwitt et al. "Distributed Raman Amplifiers for Long Haul Transmission Systems." IEEE. 1998. pp. 251–252.*

Qian et al. Fiber Raman Amplifications with Dispersion Compensating Fibers. OSA TOPS vol. 44, pp. 36–43. 2001.*

Okuno et al. Nonlinear–fiber–based discrete Raman amplifier with sufficiently suppressed degradation of WDM signal quality. OSA TOPS vol. 44, pp. 72–74. 2001.*

Masuda et al. Ultra Wide–Band Raman Amplification with a Total Gain–Bandwidth of 132 nm of Two Gain–Bands around 1.5 micrometers. ECOC '99, Sep. 26–30, 1999. pp . II–146 to II–147.*

Sugizaki, et al., Slope Compensating DCF for S–band Raman Amplifier, OSA TOPS vol. 60, Optical Amplifiers and Their Applications, Nigel Jolley, John D. Minelly, and Yoshiaki Nakano, eds., 2001 Optical Society of America, pp. 49–53.

Vasilyev, et al., Pump intensity noise and ASE spectrum of Raman amplification in non–zero dispersion–shifted fibers, reprinted from the Optical Amplifiers and Their Applications Conference, 2001 Technical Digest, 2001 Optical Society of America, pp. 57–59.

Hansen et al., "Repeaterless transmission experiment employing dispersion", 21st European Conference on Optical Communication, vol. 2, 1 page, Sep. 17–21, 1995.

Nissov et al., "100 Gb/s (10×10Gb/s) WDM Transmission Over 7200 km Using Distributed Raman Amplification," European Conference on Optical Communications, paper PD–9, pp. 9–12, Sep. 1997.

Hansen et al.; "Loss compensation in dispersion compensating fiber modules by Raman amplification," Optical Fiber Conference OFC'98, paper TuD1, Technical Digest, San Jose, CA, pp. 20–21, Feb. 1998.

Lee et al., "Bidirectional transmission of 40 Gbit/s WDM signal over 100km dispersion shifted fibre," Electronics Letters, vol.34, No. 3, pp. 294–295, Feb. 5, 1998.

Okuno et al., "Generation of Ultra–Broad–Band Supercontinuum by Dispersion–Flattened and Decreasing Fiber," IEEE Photonics Technology Letters, vol. 10, No. 1, pp. 72–74, Jan. 1998.

Masuda et al., "Ultrawide 75–nm 3–dB Gain–Band Optical Amplification with Erbium–Doped Fluoride Fiber Amplifiers and Distributed Raman Amplifiers," IEEE Photonics Technology Letters, vol. 10, No. 4, pp. 516–518, Apr. 1998.

Emori et al., "Less than 4.7 dB Noise Figure Broadband In–Line EDFA with A Raman Amplified–1300 ps/nm DCF Pumped by Multi–channel WDM Laser Diodes," OSA Conference, paper PD3–1–5, Vail, CO, Jul. 1998.

Kawai et al., "Ultrawide, 75–nm 3–dB gain–band optical amplifier utilizing erium–doped fluoride fiber and Raman fiber," OFC Technical Digest, pp. 32–34, 1998.

Becker et al., "Erbium Doped Fiber Amplifiers Fundamentals and Technology," Academic Press, pp. 55–60, 1999.

Masuda et al., "Wide–Band and Gain–Flattened Hybrid Fiber Amplifier Consisting of an EDFA and a Multiwavelength Pumped Raman Amplifier," IEEE Photonics Technology Letters, vol. 11, No. 6, pp. 647–649, Jun. 1999.

Kawai, et al. "Wide–Bandwidth and Long–Distance WDM Transmission Using Highly Gain–Flattened Hybrid Amplifier," IEEE Photonics Technology Letters, vol. 11, No. 7, pp. 886–888, Jul. 1999.

Yun et al., "Dynamic Erbium–Doped Fiber Amplifier Based on Active Gain Flattening with Fiber Acoustooptic Tunable Filters," IEEE Photonics Technology Letters, vol. 11, No. 10, pp. 1229–1231, Oct. 1999.

Mikkelsen et al., "160 Gb/s TDM Transmission Systems," ECOC, 4 pages, 2000.

Nielsen et al., "3.28 Tb/s (82×40 Gb/s) transmission over 3×100 km nonzero–dispersion fiber using dual C– and L–band hybrid Raman/Erbium–doped inline amplifiers," OFCC 2000, pp. 1229–1231, Mar. 7–10, 2000.

Pending patent application; U.S. Ser. No. 09/811,067, entitled "Method and System for Reducing Degredation of Optical Signal to Noise Ratio", Filed Mar. 16, 2001.

Pending patent application; U.S. Ser. No. 09/811,103; entitled "System and Method for Wide Band Raman Amplification", Filed Mar. 16, 2001.

Pending patent application; U.S. Ser. No. 09/916,454; entitled "System and Method for Controlling Noise Figure", Filed Jul. 27, 2001.

Pending patent application; U.S. Ser. No. 10/100,588; entitled "Electro–Absorption Based Modulation", Filed Mar. 15, 2002.

Pending patent application, U.S. Ser. No. 09/768,367, entitled "All Band Amplifier", Filed Jan. 22, 2001.

Pending patent application; U.S. Ser. No. 09/766,489; entitled "Nonlinear Polarization Amplifiers in Nonzero Dispersion Shifted Fiber", Filed Jan. 19, 2001.

Pending patent application; U.S. Ser. No. 09/800,085; entitled "Dispersion Compensating Nonlinear Polarization Amplifier", Filed Mar. 5, 2001.

Pending patent application; U.S. Ser. No. 09/765,972; entitled "S+ Band Nonlinear Polarization Amplifiers", Filed Jan. 19, 2001.

Pending patent application; U.S. Ser. No. 10/003,199; entitled "Broadband Amplifier and Communication System", Filed Oct. 30, 2001.

Pending patent application; U.S. Ser. No. 10/005,472; entitled "Multi–Stage Optical Amplifier and Broadband Communcation System", Filed Nov. 6, 2001.

Pending patent application; U.S. Ser. No. 10/014,839; entitled "Multi–Stage Optical Amplifier and Broadband Communcation System", Filed Dec. 10, 2001.

Pending patent application; U.S. Ser. No. 09/990,142; entitled "Broadband Amplifier and Communication System", Filed Nov. 20, 2001.

* cited by examiner

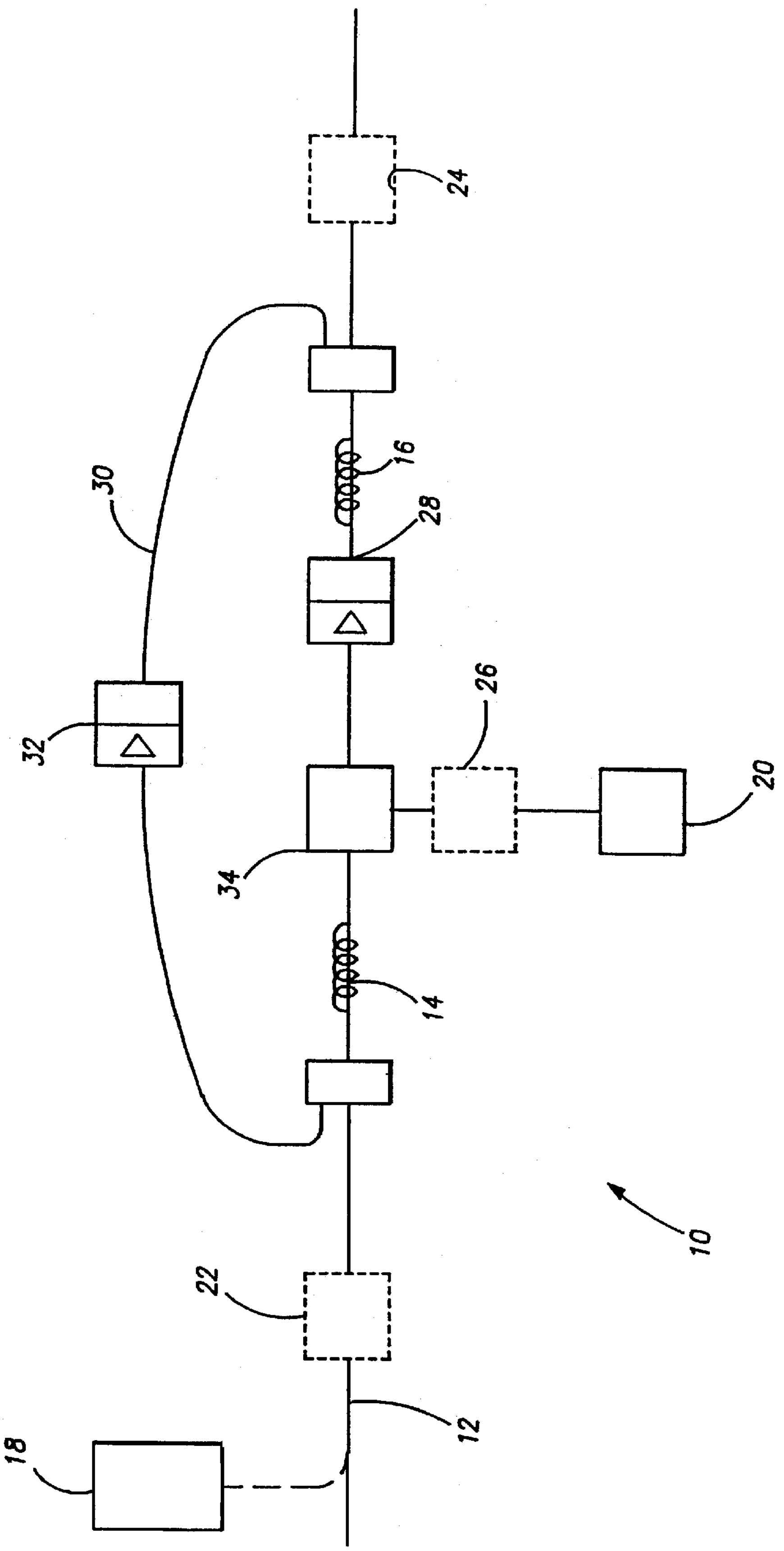


FIG. —1

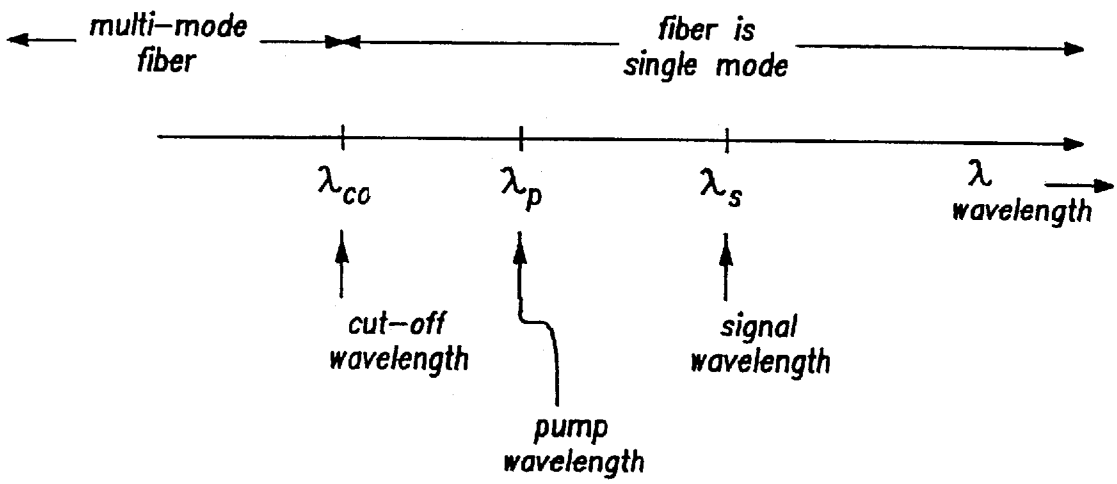

multi-mode fiber
fiber is single mode
λ_{co}
λ_p
λ_s
λ wavelength
cut-off wavelength
pump wavelength
signal wavelength

FIG.-2

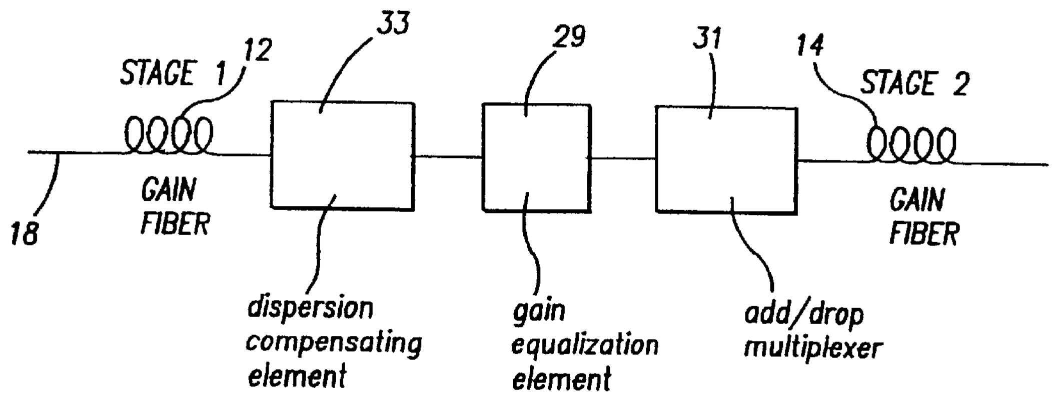

33
29
31
STAGE 1
12
14
STAGE 2
GAIN
FIBER
18
GAIN
FIBER
dispersion
compensating
element
gain
equalization
element
add/drop
multiplexer

FIG.—3

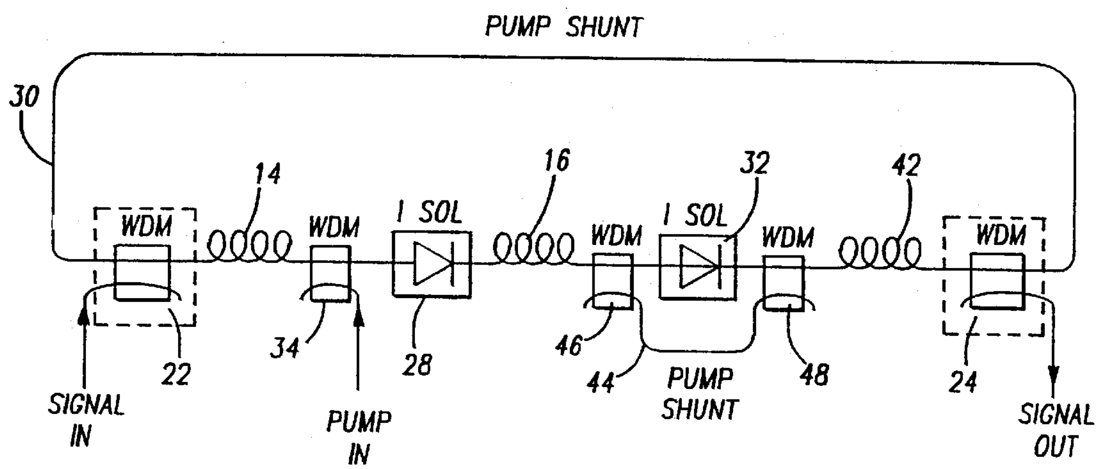


FIG. −4 (Continued)

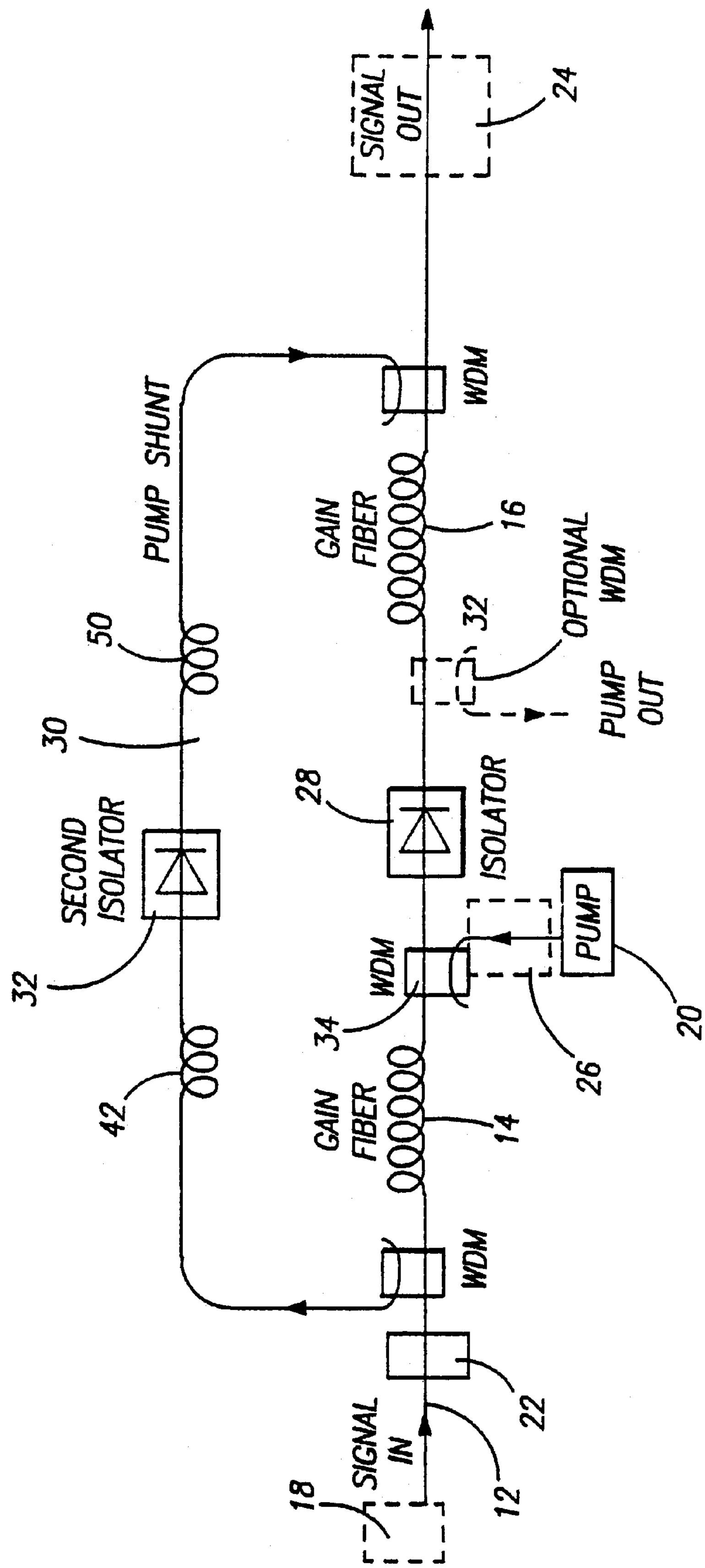
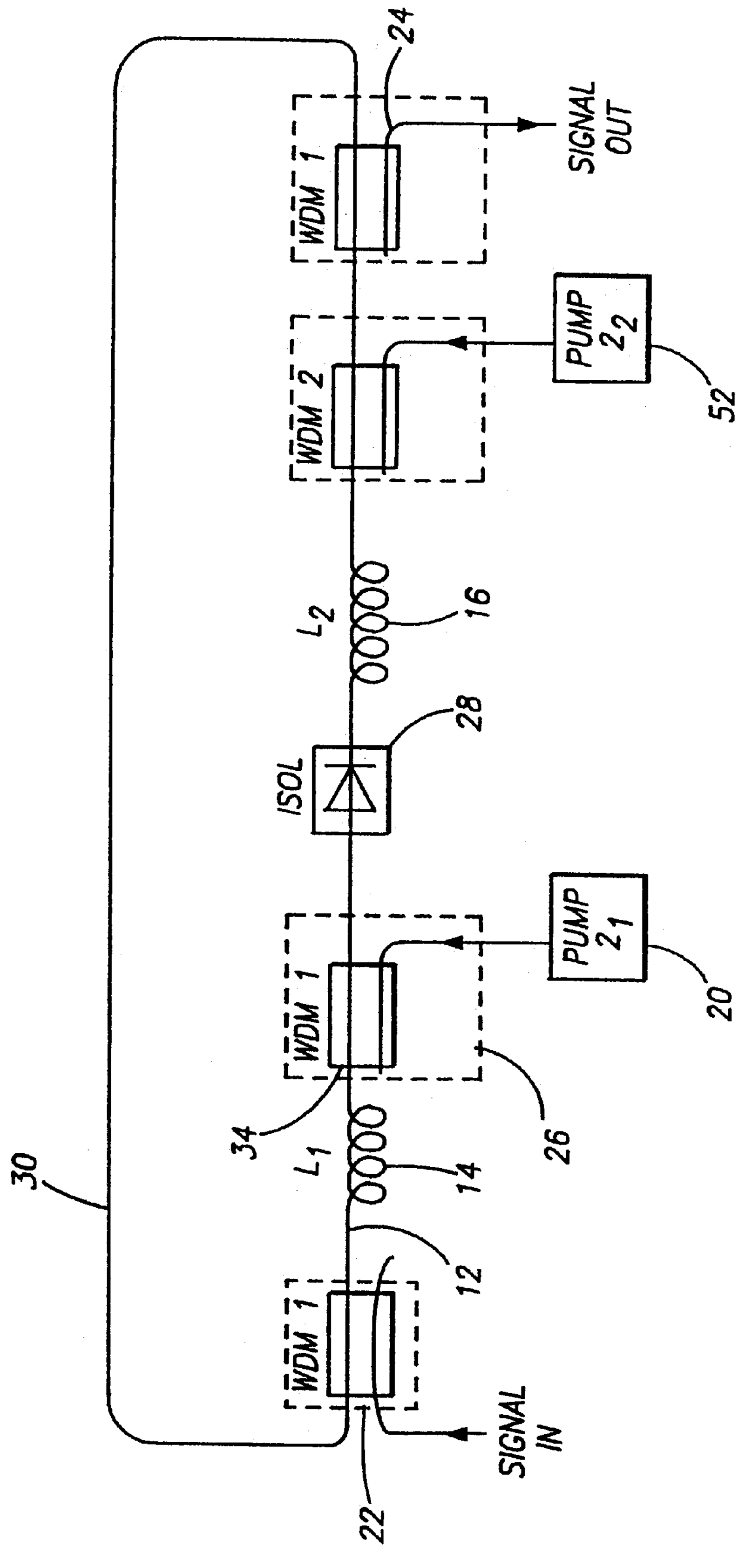

SIGNAL OUT
24
WDM
PUMP SHUNT
GAIN FIBER
16
OPTIONAL WDM
32
50
30
PUMP OUT
28
ISOLATOR
SECOND ISOLATOR
32
PUMP
WDM
34
20
26
42
GAIN FIBER
14
WDM
22
SIGNAL IN
18
12

FIG. -5



24
WDM 1
SIGNAL OUT
WDM 2
PUMP 2_2
52
L_2
16
ISOL
28
WDM 1
PUMP 2_1
20
34
L_1
14
26
30
12
WDM 1
SIGNAL IN
22

FIG. –6

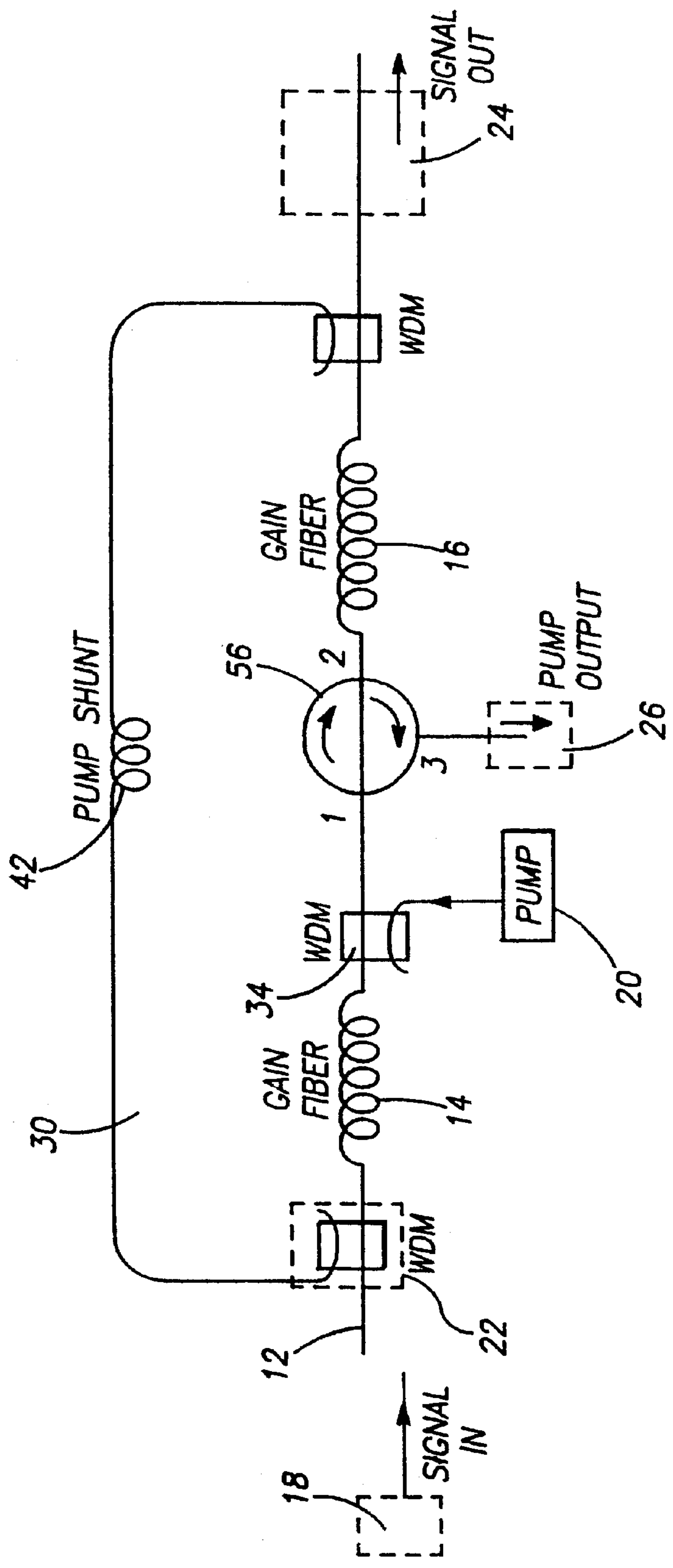
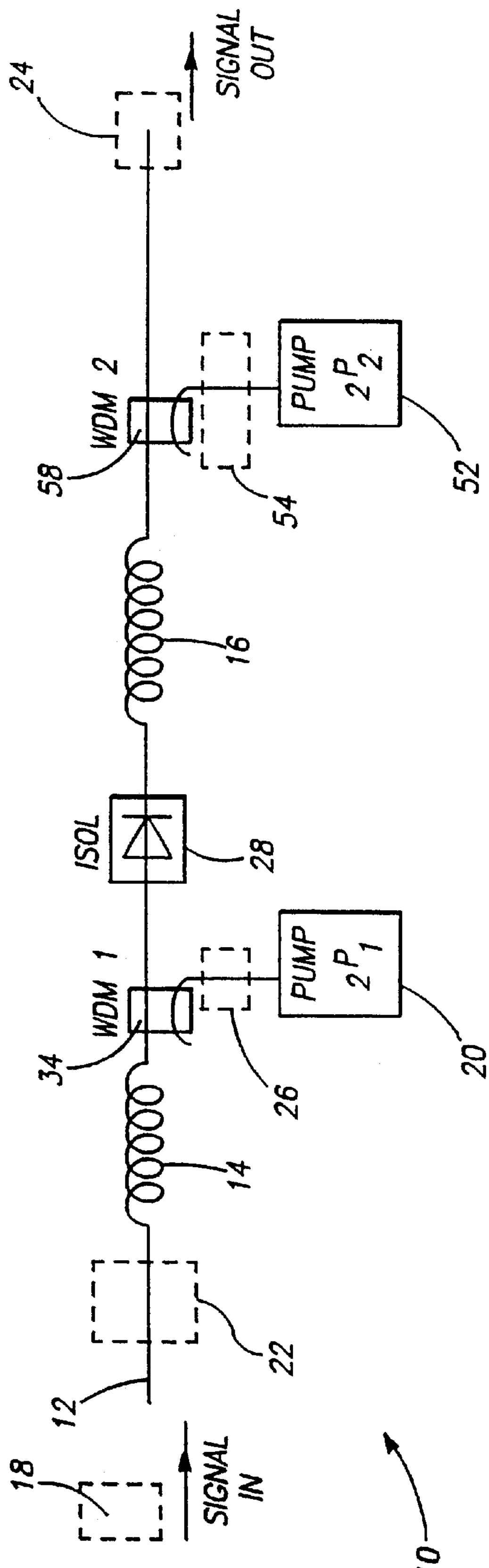

SIGNAL OUT
24
WDM
GAIN FIBER
16
PUMP OUTPUT
26
56
2
3
1
PUMP SHUNT
42
PUMP
20
WDM
34
GAIN FIBER
14
30
WDM
22
12
SIGNAL IN
18

FIG. — 7



SIGNAL OUT
24
WDM 2
PUMP
2P2
58
54
52
16
ISOL
28
WDM 1
PUMP
2P1
34
26
20
14
22
12
18
SIGNAL IN
10

FIG.—8

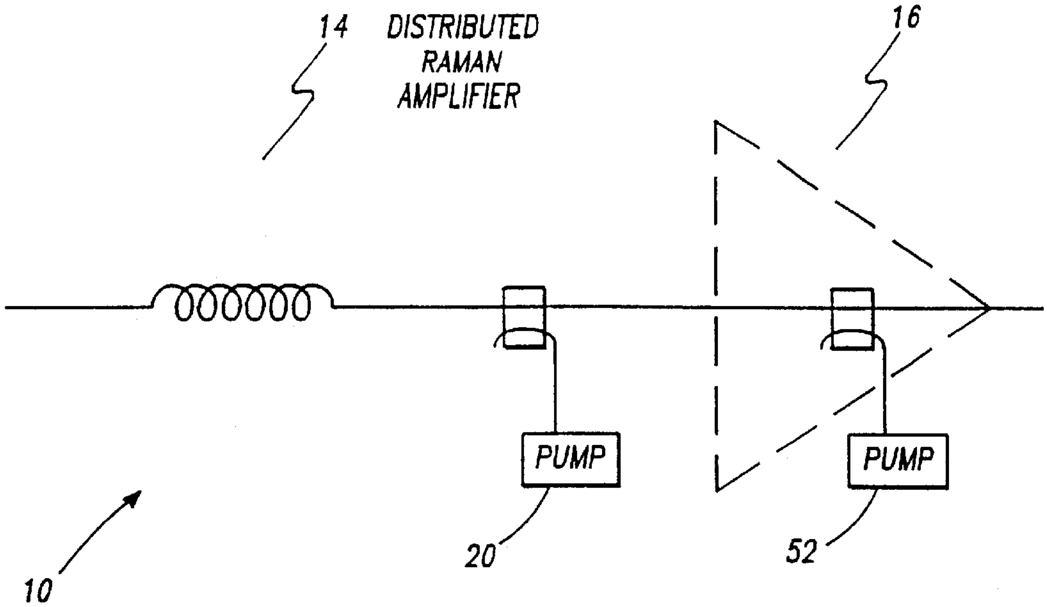

14
DISTRIBUTED RAMAN AMPLIFIER
16
PUMP
PUMP
20
52
10

FIG.—8b

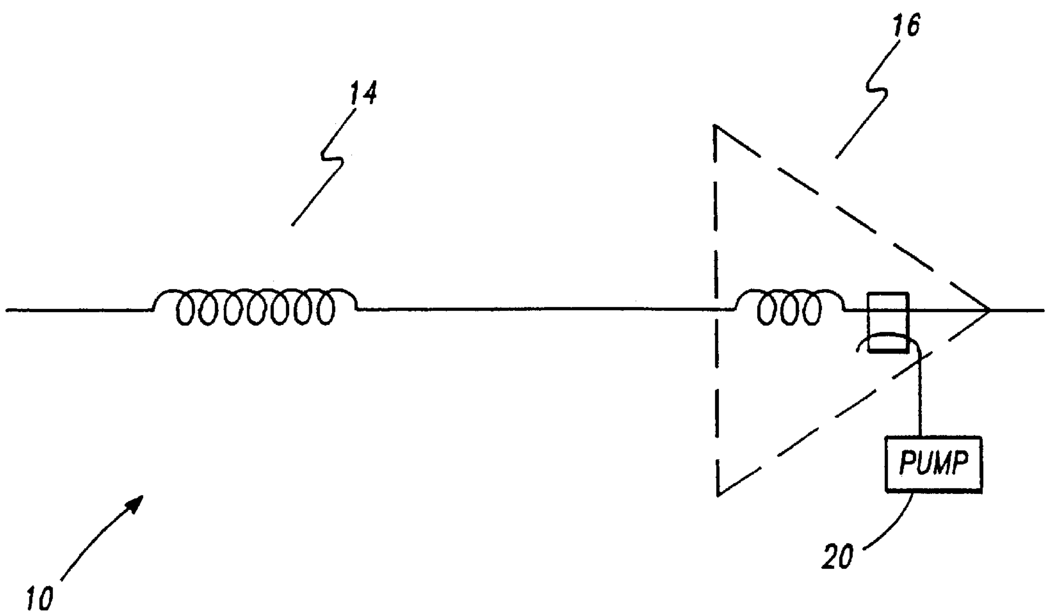

16
14
PUMP
20
10

FIG.—8c

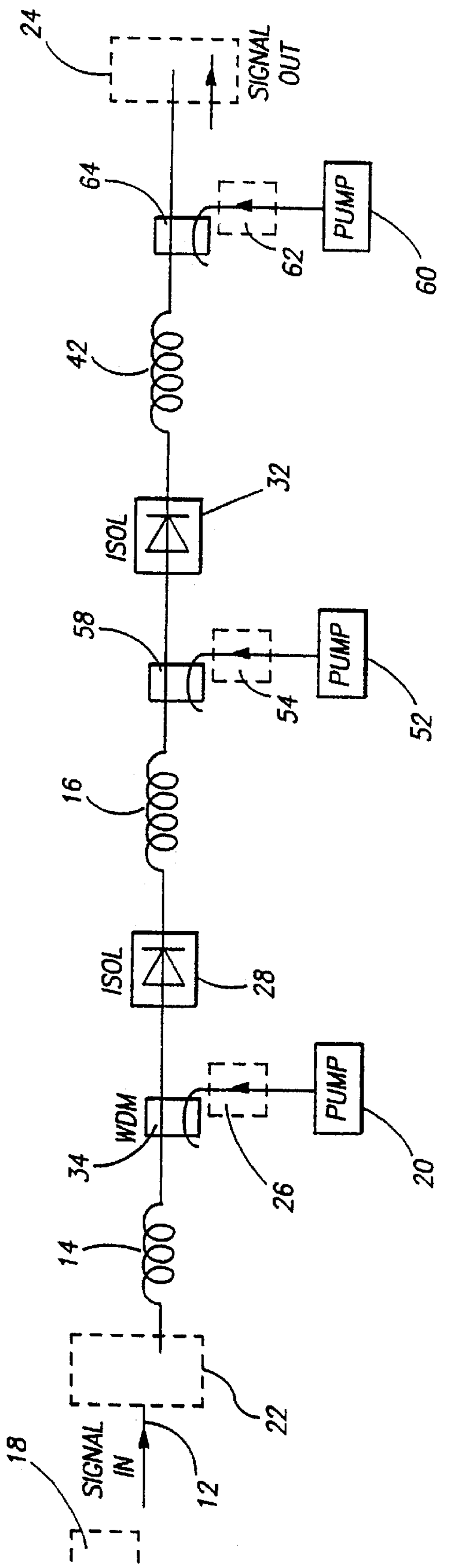

24
SIGNAL OUT
64
62
PUMP
60
42
ISOL
32
58
54
PUMP
52
16
ISOL
28
WDM
34
26
PUMP
20
14
22
SIGNAL IN
12
18

FIG. —9

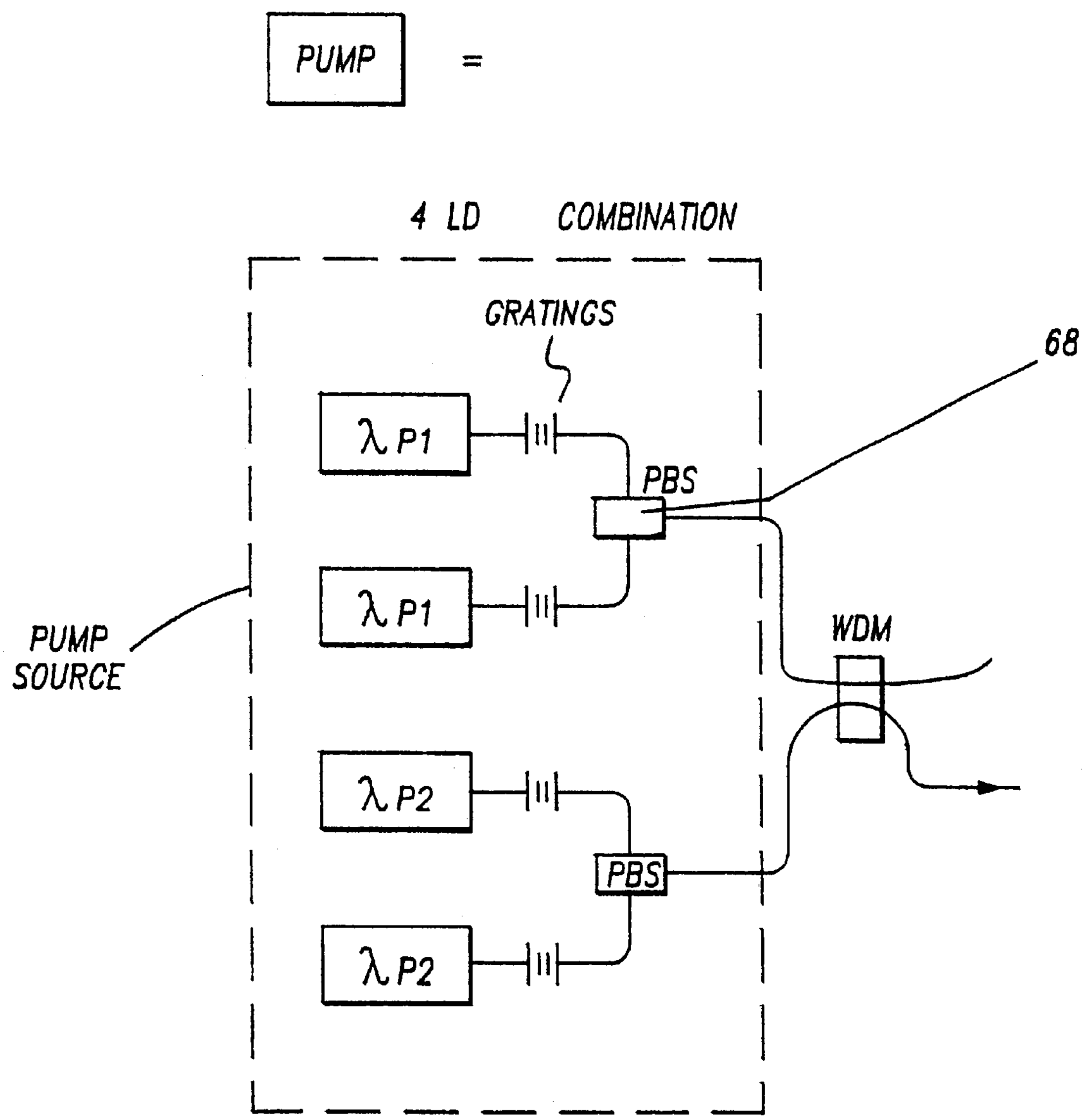

PUMP
=
4 LD COMBINATION
GRATINGS
68
λ P1
PBS
λ P1
PUMP SOURCE
WDM
λ P2
PBS
λ P2

FIG.−10

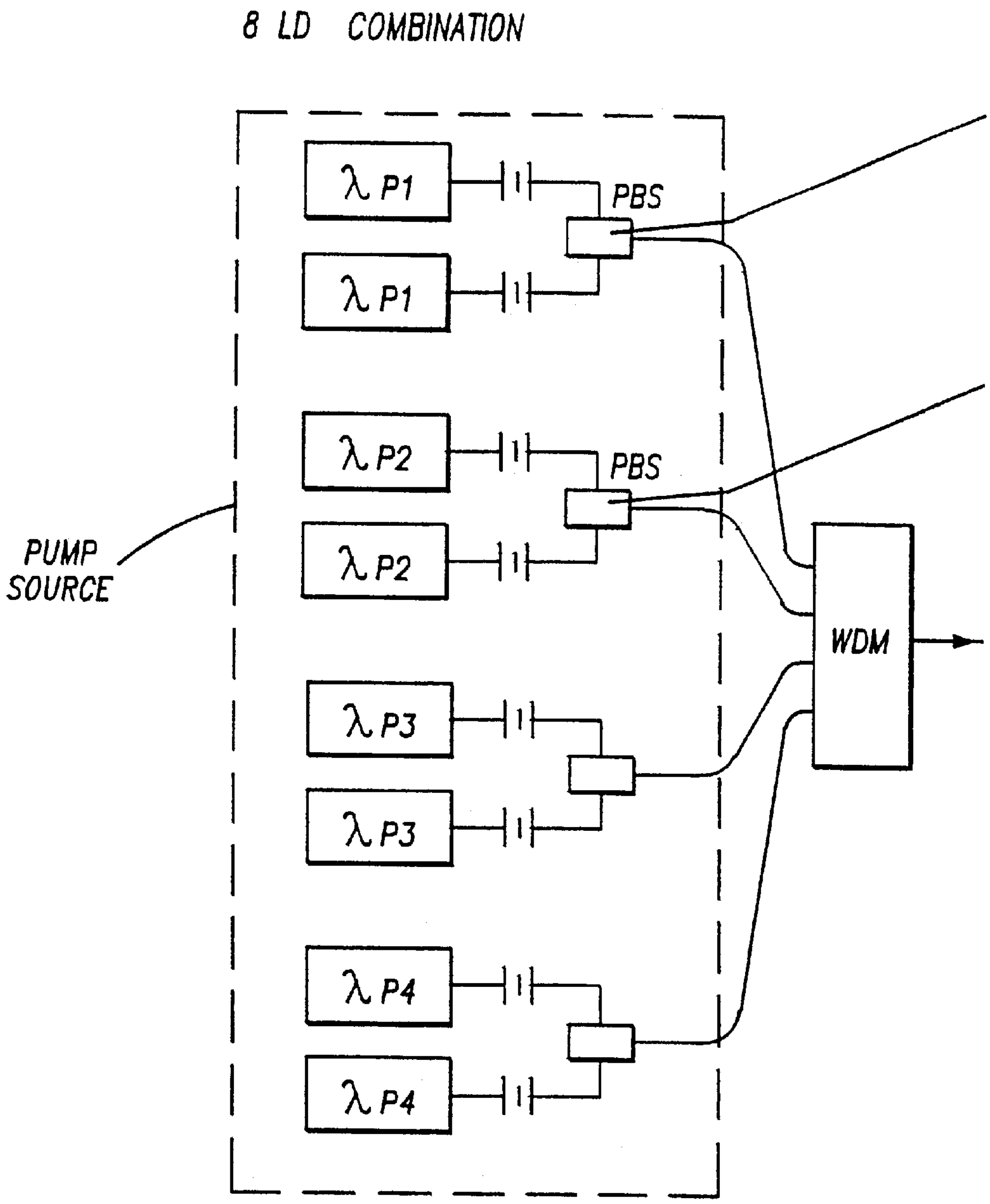

8 LD COMBINATION
66
68
λ P1
λ P1
PBS
λ P2
λ P2
PBS
PUMP SOURCE
WDM
λ P3
λ P3
λ P4
λ P4

FIG.−11

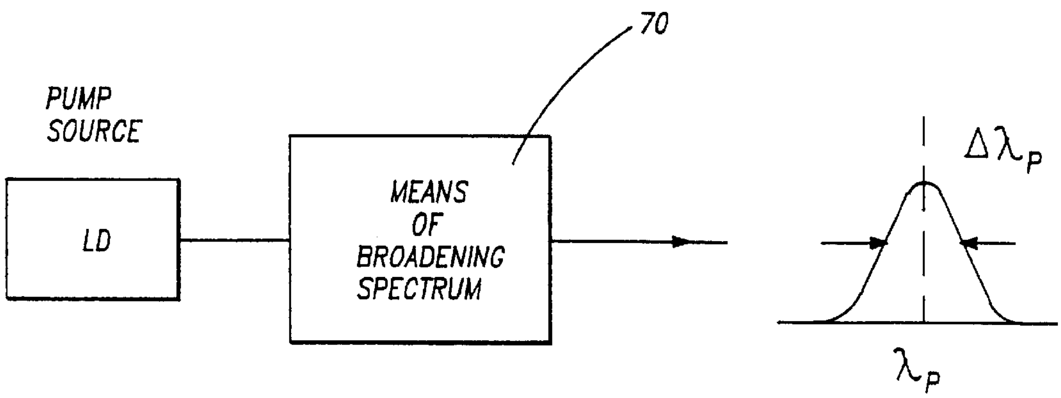

70
PUMP
SOURCE
LD
MEANS
OF
BROADENING
SPECTRUM
$\Delta\lambda_p$
λ_p

FIG.—12

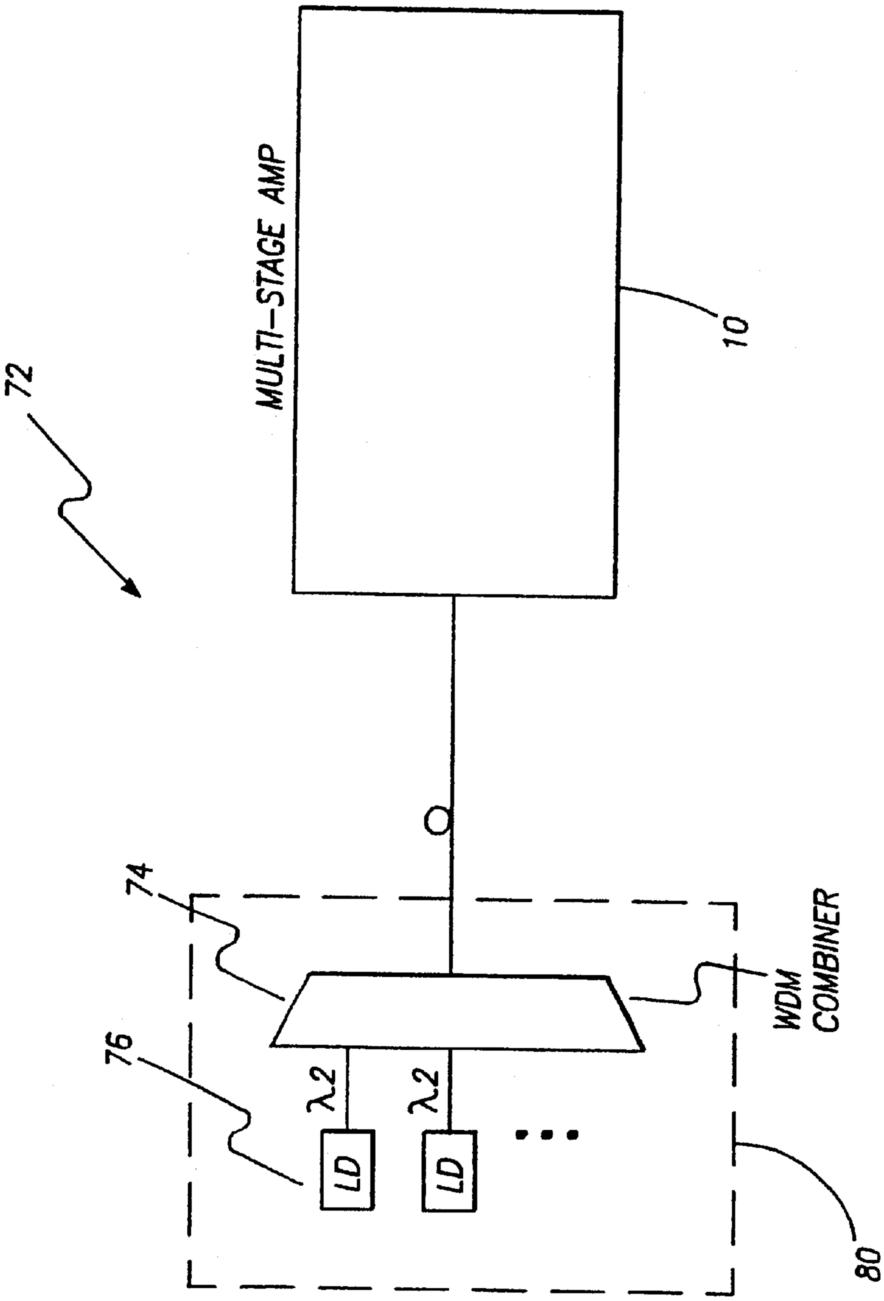


FIG. – 13

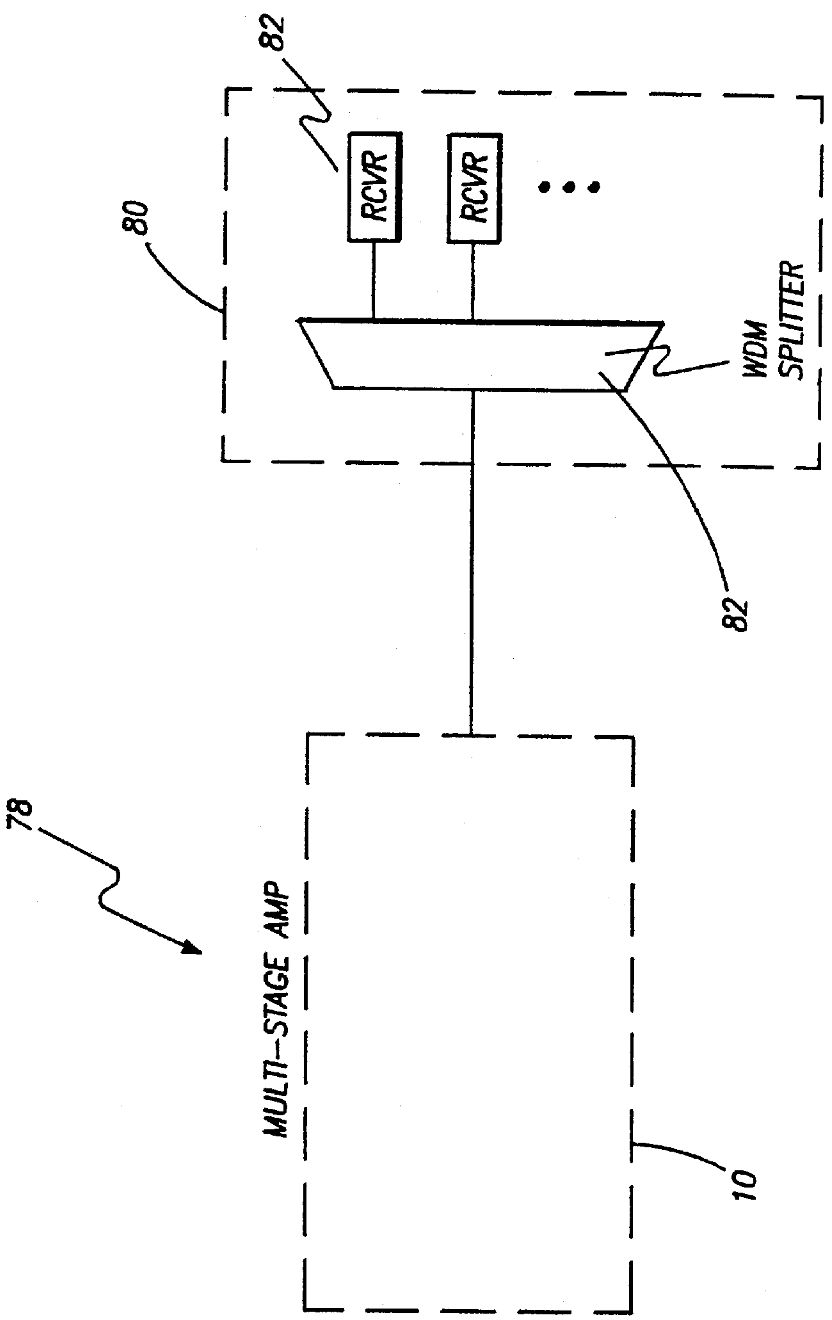


FIG. — 14

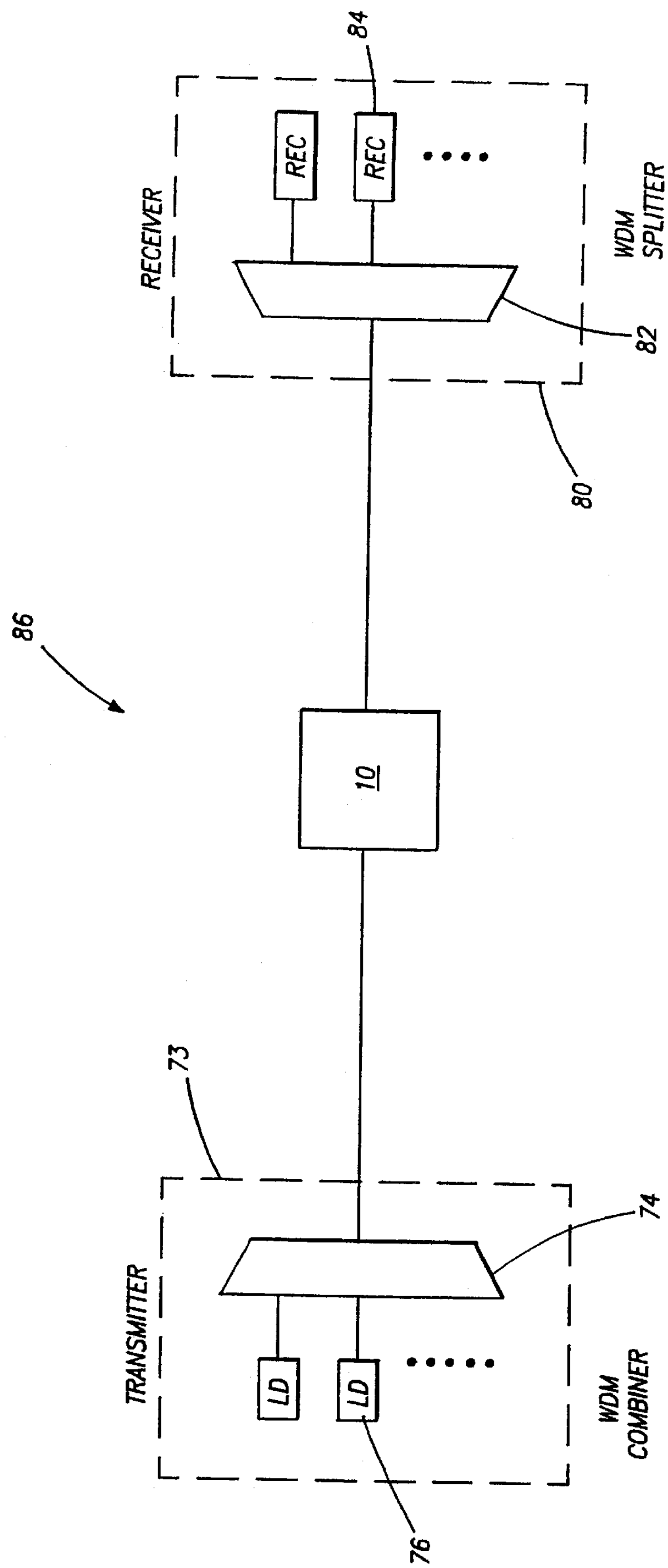

RECEIVER
REC
REC
84
WDM
SPLITTER
82
80
86
10
73
74
TRANSMITTER
LD
LD
WDM
COMBINER
76

FIG. —15

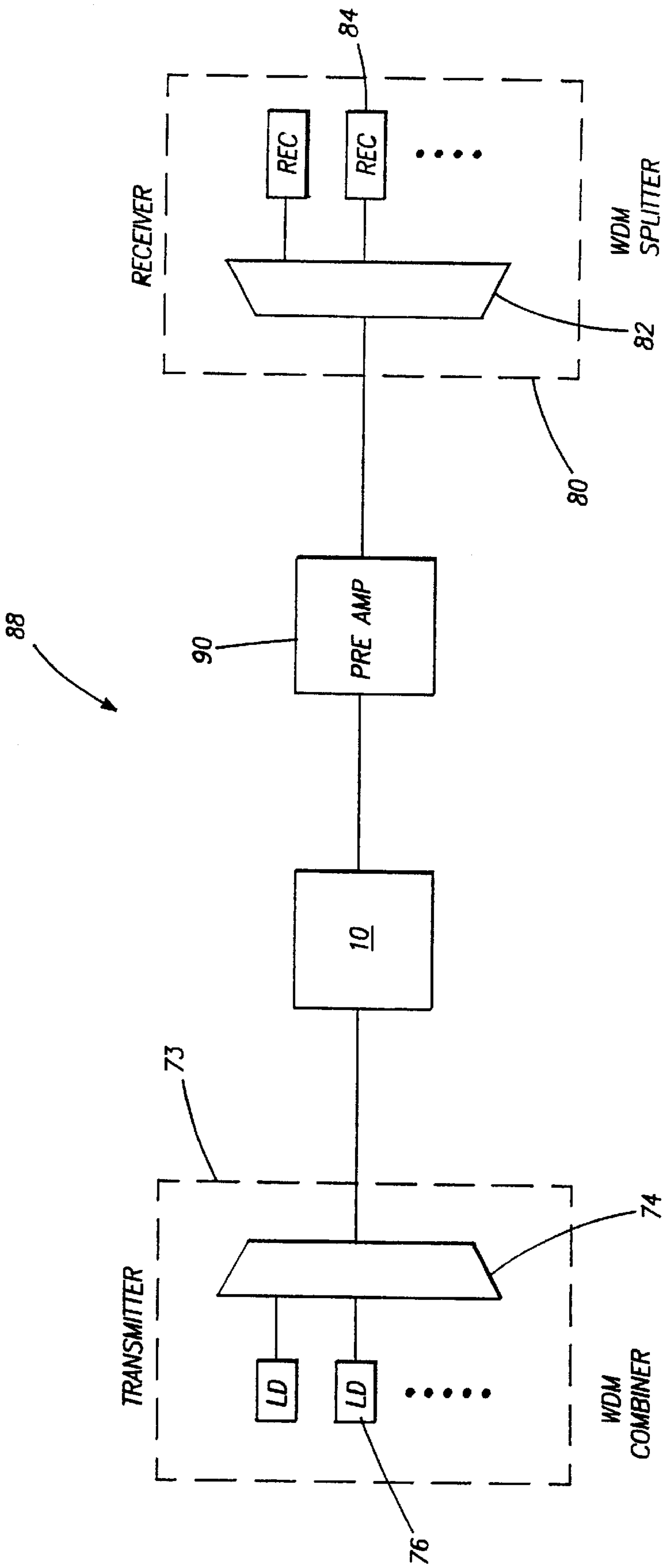

84
RECEIVER
REC
REC
WDM
SPLITTER
82
80
88
90
PRE AMP
10
73
74
TRANSMITTER
LD
LD
WDM
COMBINER
76

FIG. — 16

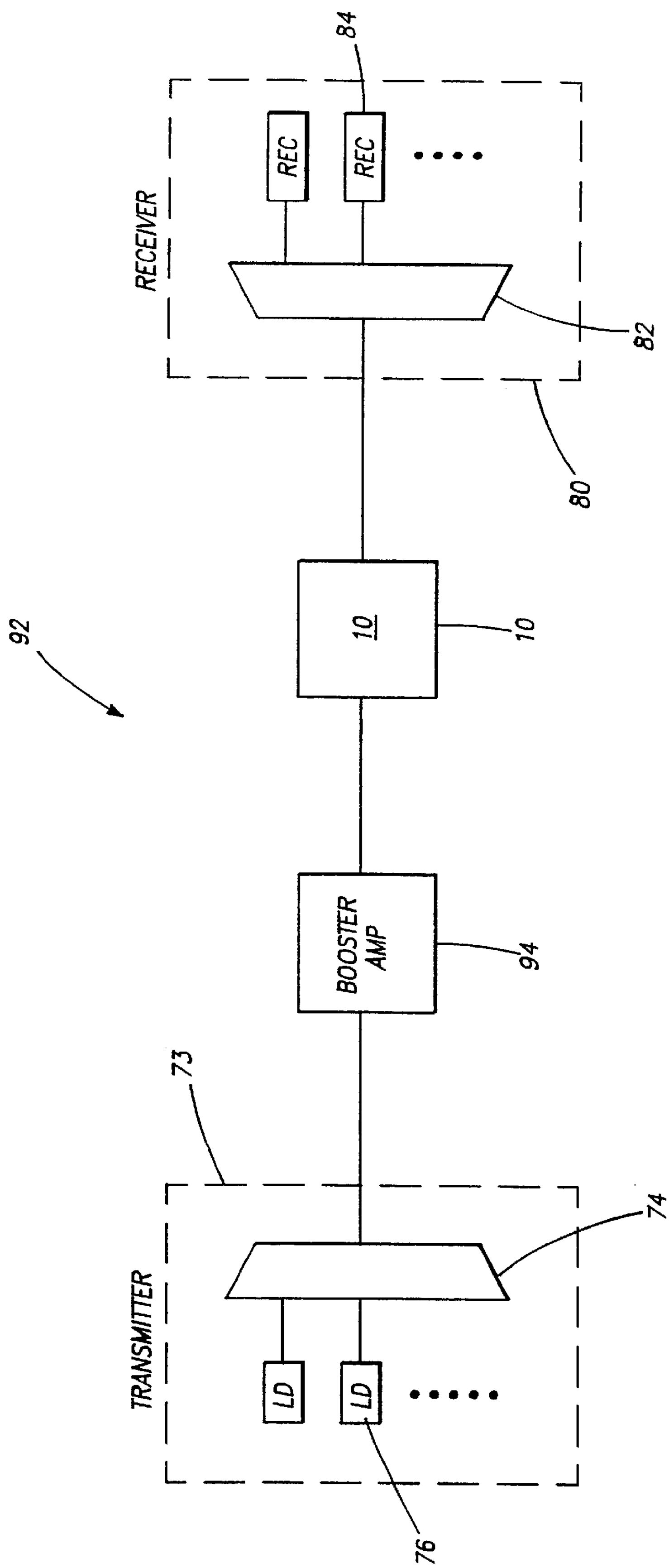

84
RECEIVER
REC
REC
82
80
92
10
10
BOOSTER AMP
94
73
74
TRANSMITTER
LD
LD
76

FIG. — 17

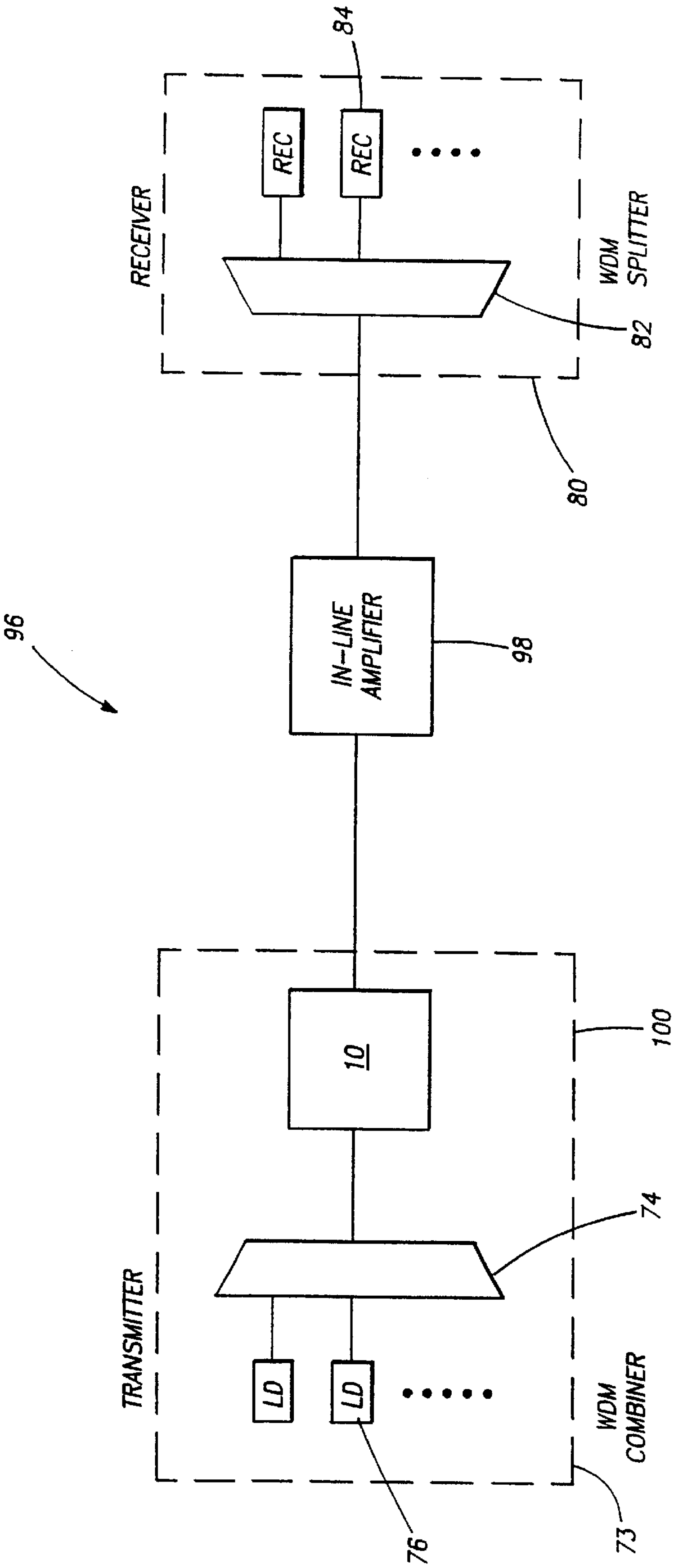

RECEIVER
REC
REC
84
WDM SPLITTER
82
80
96
IN-LINE AMPLIFIER
98
10
100
TRANSMITTER
LD
LD
74
WDM COMBINER
76
73

FIG. — 18

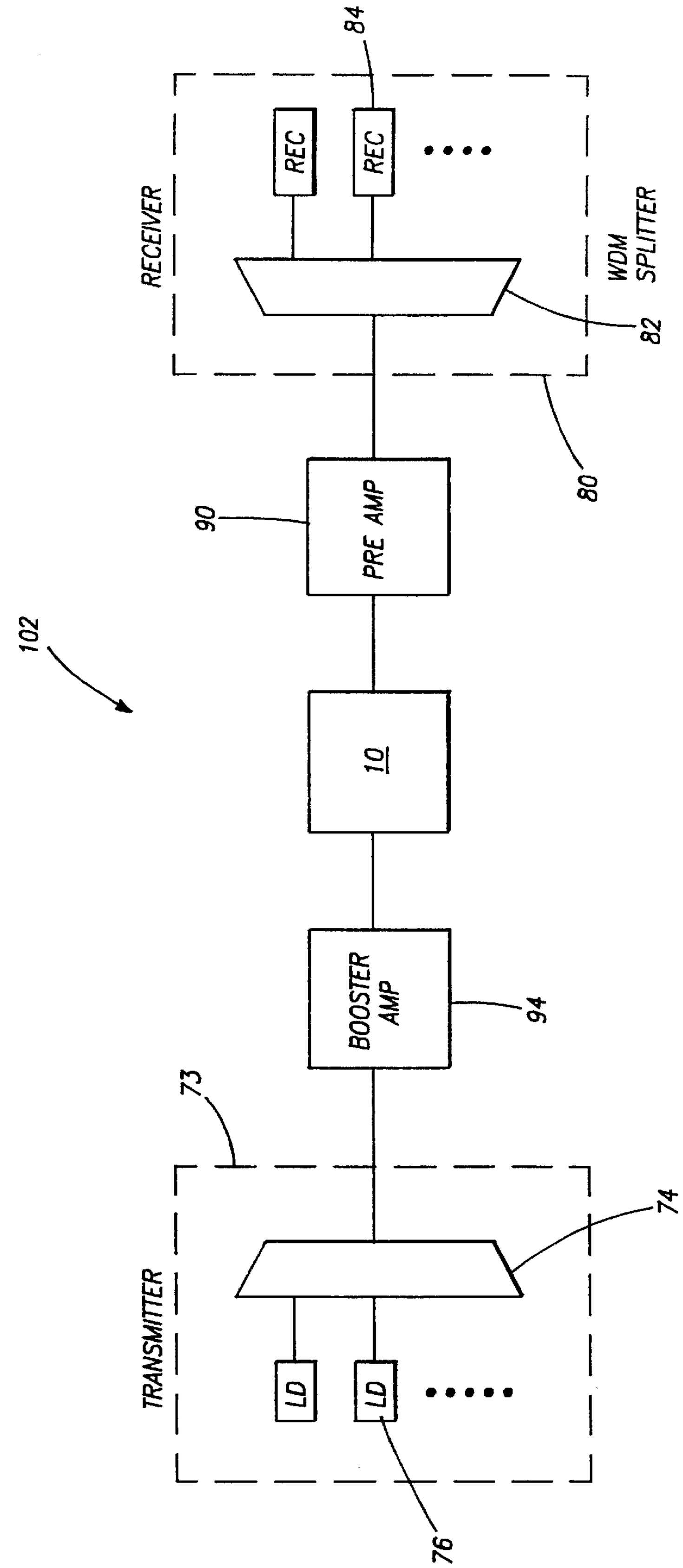

RECEIVER
REC
REC
84
WDM SPLITTER
82
80
PRE AMP
90
102
10
BOOSTER AMP
94
73
74
TRANSMITTER
LD
LD
76

FIG. — 19

MULTI-STAGE OPTICAL AMPLIFIER AND BROADBAND COMMUNICATION SYSTEM

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. application Ser. No. 09/471,753, filed Dec. 23, 1999, now U.S. Pat. No. 6,359,725 which is a continuation-in-part of Provisional Application Serial No. 60/089,426, filed Jun. 16, 1999, and a continuation-in-part of application Ser. No. 09/471,747, filed Dec. 23, 1999, now U.S. Pat. No. 6,335,820.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to multi-stage optical amplifiers, and more particularly to broadband communication systems that include one or more multi-stage optical amplifiers.

2. Description of the Related Art

The demand for bandwidth continues to grow exponentially on fiber-optic superhighways due to applications such as data communications and the internet. Consequently, there is much effort at exploiting the bandwidth of optical fibers by using higher speeds per channel. Examples include time-division multiplexed systems-and wavelength-division multiplexing (WDM).

Most fiber-optic networks currently deployed use standard single-mode fiber or dispersion-shifted fiber (DSF). Standard fiber has a zero dispersion wavelength around 1310 nm, and the dispersion is primarily resulting from the inherent glass dispersion. Currently, most of the terrestrial network in the US and the world is based on standard fiber.

With DSF, waveguide dispersion is used to shift the zero dispersion wavelength to longer wavelengths. A conventional DSF has a zero dispersion wavelength at 1550 nm, coinciding with the minimum loss in a fused silica fiber. However, the zero dispersion wavelength can be shifted around by varying the amount of waveguide dispersion added. DSF is used exclusively in two countries, Japan and Italy, as well as in new long-haul links.

The limiting factors for a fiber-optic transmission line include loss, dispersion and gain equalization. Loss refers to the fact that the signal attenuates as it travels in a fiber due to intrinsic scattering, absorption and other extrinsic effects such as defects. Optical amplifiers can be used to compensate for the loss. Dispersion means that different frequencies of light travel at different speeds, and it comes from both the material properties and waveguiding effects. When using multi-wavelength systems and due the non-uniformity of the gain with frequency, gain equalization is required to even out the gain over the different wavelength channels.

The typical solution to overcoming these limitations is to periodically place in a transmission system elements to compensate for each of these problems. For example, a dispersion compensator can be used to cancel the dispersion, an optical amplifier used to balance the loss and a gain equalization element used to flatten the gain. Examples of dispersion compensators include chirped fiber gratings and dispersion compensating fiber (DCF). Examples of optical amplifiers include erbium-doped fiber amplifiers (EDFAs), Raman amplifiers, and non-linear fiber amplifiers (NLFAs).

Another problem that arises in WDM systems is interaction or cross-talk between channels through non-linearities in the fiber. In particular, four-wave mixing (4WM) causes exchange of energy between different wavelength channels, but 4WM only phase matches near the zero dispersion wavelength. Consequently, if a fiber link is made from conventional DSF, it is difficult to operate a WDM system from around 1540–1560 nm. This turns out to be quite unfortunate because typical EDFA's have gain from 1535–1565 nm, and the more uniform gain band is near 1540–1560 nm. A second fiber nonlinearity that can be troublesome is modulation instability (MI), which is 4WM where the fiber's nonlinear index-of-refraction helps to phase match. However, MI only phase matches when the dispersion is positive or in the so-called soliton regime. Therefore, MI can be avoided by operating at wavelengths shorter than the zero dispersion wavelength.

As the bandwidth utilization over individual fibers increases, the number of bands used for transmission increases. For WDM systems using a number of bands, additional complexities arise due to interaction between and amplification in multi-band scenarios. In particular, particular system designs are needed for Raman amplification in multi-band transmission systems. First, a new nonlinearity penalty arises from the gain tilt from the Raman effect between channels. This arises because long wavelength channels tend to rob energy from the short wavelength channels. Therefore, a means of minimizing the gain tilt on existing channels with the addition of new WDM channels is required.

To minimize both the effects of 4WM and Raman gain tilt, another technical strategy is to use distributed Raman amplification. In a WDM system with multi-bands, a complexity arises from interaction between the different pumps along the transmission line.

There is a need for greater bandwidth for broadband communication systems. A further need exists for broadband communication systems with reduced loss. Yet another need exists for broadband communication systems in the short wavelength region (S-band) covering the wavelength range of approximately 1430–1530 nm. Another need exists for broadband communication systems with improved dispersion compensation.

SUMMARY OF THE INVENTION

Accordingly, it is an object of the present invention to provide improved multi-stage optical amplifiers and broadband communication systems.

Another object of the present invention is to provide multi-stage optical amplifiers and broadband communication systems with greater bandwidth.

Yet another object of the present invention is to provide multi-stage optical amplifiers and broadband communication systems in the S band.

A further object of the present invention is to provide multi-stage optical amplifiers and broadband communication systems that use standard fiber and DSF with different zero dispersion wavelengths.

Another object of the present invention is to provide a multi-stage optical amplifier and broadband communication system that combines the C and S bands.

Yet another object of the present invention is to provide multi-stage optical amplifiers and broadband communication systems that combine the C, S and L bands.

A further object of the present invention is to provide multi-stage optical amplifiers and broadband communication systems with gain tilt control.

It is yet another object of the present invention to provide WDM systems over DSF links by using the "violet" band in

Raman amplifiers with dispersion compensating fiber to avoid nonlinearity limitations from 4WM and MI.

These and other objects of the present invention are achieved in a multi-stage optical amplifier that has an optical fiber. The optical fiber includes at least a first Raman amplifier fiber and a second Raman amplifier fiber. The optical fiber is configured to be coupled to at least one signal source that produces at least a signal wavelength λ_s and at least two pump sources that collectively produce a pump beam of wavelength λ_p. Pump wavelength λ_p is less than signal wavelength λ_s. Signal input, signal output and a first pump input port are each coupled to the optical fiber. The first Raman amplifier fiber is positioned between the signal input port and the pump input port. The second Raman amplifier fiber is positioned between the pump input port and signal output port. A second pump input port is coupled to the optical fiber and positioned between the second Raman amplifier fiber and the signal output port. A first lossy member is positioned between the pump input port and the signal output port. The lossy member is lossy in at least one direction so that passage of the pump radiation of wavelength λ_p from the second to the first length of amplifier fiber is substantially blocked. The signal flows in a first direction and the pump beam flows in a reverse direction relative to the first direction.

In another embodiment, the present invention is a broadband communication system with a transmitter and a receiver. An optical fiber is coupled to the transmitter and receiver. The optical fiber includes at least a first Raman amplifier fiber and a second Raman amplifier fiber. The optical fiber is configured to be coupled to at least one signal source that produces at least a signal wavelength λ_s and at least two pump sources that collectively produce a pump beam of wavelength λ_p. Pump wavelength λ_p is less than signal wavelength λ_s. Signal input, signal output and a first pump input port are each coupled to the optical fiber. The first Raman amplifier fiber is positioned between the signal input port and the pump input port. The second Raman amplifier fiber is positioned between the pump input port and signal output port. A second pump input port is coupled to the optical fiber and positioned between the second Raman amplifier fiber and the signal output port. A first lossy member is positioned between the pump input port and the signal output port. The lossy member is lossy in at least one direction so that passage of the pump radiation of wavelength λ_p from the second to the first length of amplifier fiber is substantially blocked.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic diagram of one embodiment of a multi-stage optical amplifier of the present invention that includes a pump shunt.

FIG. **2** illustrates that the cutoff wavelength of the fiber used with the present invention should be shorter than the pump and signal wavelengths.

FIG. **3** is a schematic diagram illustrating the inclusion of a dispersion compensating element, a gain equalization element and an add/drop multiplexer to the multi-stage optical amplifier of the present invention.

FIG. **4** is a schematic diagram of another embodiment of a multi-stage optical amplifier of the present invention that includes two pump shunts.

FIG. **5** is a schematic diagram of another embodiment of a multi-stage optical amplifier of the present invention that includes a pump shunt and four lengths of amplifier fiber.

FIG. **6** is a schematic diagram of one embodiment of a multi-stage optical amplifier of the present invention that includes a pump shunt and two pump sources.

FIG. **7** is a schematic diagram of one embodiment of a multi-stage optical amplifier of the present invention that includes a pump shunt and a circulator.

FIG. **8**(*a*) is a schematic diagram of another embodiment of a multi-stage optical amplifier of the present invention that includes two lengths of Raman amplifier fiber and two pump sources.

FIG. **8**(*b*) is a schematic diagram of an embodiment of the present invention with a discrete and a distributed amplifier; where distributed amplification is added with only counter-propagating Raman pumps.

FIG. **8**(*c*) is a schematic diagram of an embodiment of the present invention similar to FIG. **8**(*b*) in which mid-span access is not available but bi-directional pumping is allowed.

FIG. **9** is a schematic diagram of another embodiment of a multi-stage optical amplifier of the present invention that includes three lengths of Raman amplifier fiber and three pump sources.

FIG. **10** is a schematic diagram illustrating four pump source whose outputs are combined using wavelength and polarization multiplexing.

FIG. **11** is a schematic diagram illustrating eight pump source whose outputs are combined using wavelength and polarization multiplexing.

FIG. **12** is a schematic diagram illustrating that Brillouin threshold for a laser diode pump source can be minimized with the inclusion of a spectrum broadening device.

FIG. **13** is a schematic diagram of a broadband booster amplifier embodiment of the present invention.

FIG. **14** is a schematic diagram of a broadband pre-amplifier embodiment of the present invention.

FIG. **15** is a schematic diagram of one embodiment of a broadband communication system of the present invention.

FIG. **16** is a schematic diagram of another embodiment of a broadband communication system of the present invention.

FIG. **17** is a schematic diagram of another embodiment of a broadband communication system of the present invention.

FIG. **18** is a schematic diagram of another embodiment of a broadband communication system of the present invention.

FIG. **19** is a schematic diagram of another embodiment of a broadband communication system of the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

One embodiment of the present invention, as illustrated in FIG. **1**, is a multi-stage optical amplifier **10** with an optical fiber **12** including a first length of amplifier fiber **14** and a second length of amplifier fiber **16**. Optical fiber **12** is configured to be coupled to a signal source **18** that produces at least a signal wavelength λ_s and a pump source **20** that produces a pump wavelength λ_p. Pump wavelength λ_p is less than signal wavelength λ_s. Signal input port **22**, signal output port **24** and pump input port **26** are each coupled to optical fiber **12**. A first lossy member **28** is coupled to optical fiber **12** and positioned between the first and second lengths of amplifier fiber **14** and **16** respectively. A pump shunt **30** is coupled to signal input port **22** and signal output port **24**. Optionally, a second lossy member **32** is coupled to pump shunt **30**. Pump shunt **30** can be an optical fiber that is integral with optical fiber **12** or a separate optical fiber.

Pump beam λ_p propagates towards signal input port **22** from first length of amplifier fiber **14** and away from signal input port **22** to second length of amplifier fiber **16**.

First and second lengths of amplifier fiber **14** and **16** each preferably have a length greater than or equal to 200 m. Pump wavelength λ_p is preferably in the range of 1300 nm to 1530 nm, and the signal wavelength can be in the range of 1430 to 1530 nm. Suitable pump sources **20** include but are not limited to laser diodes (LD's), solid state lasers, fiber-based cascaded Raman wavelength shifters, cladding pumped fiber lasers and the like.

First lossy member **28** can be an optical isolator, an add/drop multiplexer. a gain equalization member, a dispersion compensation element and the like. One or both of first and second lengths of amplifier fiber **14** and **16** can be Raman amplifiers. Lossy elements **28** can also be placed before and after first and second lengths of amplifier fiber **14** and **16** to prevent disturbance of amplifier performance from spurious reflections from the transmission line. Additionally, a second lossy element **32** can be inserted into pump shunt **30** to reduce the multi-path interference of the signal beam in amplifiers **12** and **14**.

Additionally, one or both of first and second lengths of amplifier fiber **14** and **16** can be implemented in dispersion compensating fiber (DCF). A DCF is a fiber whose zero dispersion point is shifted to wavelengths much longer than 1500 nm using the waveguide dispersion property. Consequently, DCF tend to have a small affective core area and significant germanium doping in the core, both of which lead to an enhancement of the Raman gain coefficient. DCF's are generally added periodically to a high-speed transmission link to compensate for the dispersion accumulated in the line.

In one embodiment, multi-stage optical amplifier **10** operates in a violet band between 1430 and 1530 nm. Fiber **12** is a DSF with at least one fiber non-linearity effect and a zero dispersion wavelength. In this embodiment, multi-stage optical amplifier **10** provides gain in the violet band sufficiently far from the zero dispersion wavelength to avoid non-linearity effects.

First length of amplifier fiber **14** preferably has lower noise than second length of amplifier fiber **16**. Second length of amplifier fiber **16** has a higher gain than first length of amplifier fiber **14**. In one embodiment, first length of amplifier fiber **14** has an optical noise figure of less than 8 dB, and second length of amplifier fiber **16** has a gain level of at least 5 dB.

One or more WDM couplers **34** are used to couple a pump path from the signal input port **22** to the signal output port **24**. WDM couplers **34** are designed to pass (couple over) the signal band while coupling over (passing) the pump beams. Exemplary WDM couplers **34** include fused-tapered fiber couplers, Mach-Zehnder couplers, thin-film dielectric filters, bulk diachronic elements and the like.

Signal input port **22** inputs signal λ_s which is amplified through Raman scattering when first and second lengths of amplifier fiber **14** and **16** are Raman amplifiers. The dispersion and length of the first and second lengths of amplifier fiber **14** and **16** can be selected to be of the same magnitude of dispersion-length product as the transmission link but of the opposite sign of dispersion. First and second lengths of amplifier fiber **14** and **16** are preferably made single spatial mode for pump source **20** and signal wavelengths by making the cut-off wavelength of the gain fiber shorter than the pump wavelength. In particular, the cut-off wavelength is the wavelength below which first and second lengths of amplifier fiber **14** and **16** support more than one mode or becomes multi-mode. If the pump or signal falls into the multi-mode region, then additional noise arising from the beating between different modes may arise.

As shown in FIG. **2** the fiber cut-off wavelength should be shorter than the pump wavelength λ_p. Pump wavelength λ_p is shorter than signal wavelength λ_s. Multi-stage optical amplifier **10** is pumped so the net gain equals or exceeds the sum of losses in the transmission link and first and second lengths of amplifier fiber **14** and **16**.

FIG. **3** illustrates that a dispersion compensating element **33**, gain equalization element **29** or an add/drop multiplexer **31** can be included and positioned between first and second lengths of amplifier fiber **14** and **16**.

FIG. **4** illustrates an embodiment of multi-stage optical amplifier **10** with a third length of amplifier fiber **42**. Second lossy member **32** is positioned between second and third lengths of amplifier fiber **16** and **42**. A second pump shunt is coupled to second and third WDM couplers **46** and **48**. Additional lengths of amplifier fiber can also be included.

As illustrated in FIG. **5**, multi-stage optical amplifier **10** can include a third and a fourth length of amplifier fiber **42** and **50**, respectively. In this embodiment, third and fourth lengths of amplifier fiber **42** and **50** are coupled to pump shunt **30**. Second lossy member **32** is positioned between third and fourth lengths of amplifier fiber **42** and **50**.

In another embodiment of multi-stage optical amplifier **10**, multiple pump sources are utilized. In FIG. **6**, pump source **20** is positioned between first length of amplifier fiber **14** and first lossy member **28**. A second pump source **52** is positioned between second length of amplifier fiber **16** and signal output port **24** and is coupled to a second pump input port **54**. First pump source **20** produces a pump beam of wavelength λ_{p1} and second pump source **52** produces **52** a pump beam of wavelength λ_{p2}. Wavelength λ_{p1} and wavelength λ_{p2} can be the same or different. Pump sources **20** and **44** collectively produce a pump beam of wavelength λ_p. Pump wavelength λ_p is less than a signal wavelength λ_s.

In another embodiment, illustrated in FIG. **7**, multi-stage amplifier **10** includes one or more circulators **56** to provide isolation between the first and second lengths of amplifier fiber **14** and **16**. Circulator **56** also is useful as a means of dumping the remaining pump which can be reused elsewhere for monitoring purposes.

As illustrated in FIG. **8**(*a*), multi-stage optical amplifier **10** can have an open loop configuration, In this embodiment, optical fiber **12** is pumped by a pump beam generated by pump sources **20** and **52** and first and second lengths of amplifier fiber **14** and **16** are each Raman amplifiers. Optical fiber **12** is preferably single spatial mode at both the signal and pump wavelengths. Again, wavelength λ_{p1} and wavelength λ_{p2} can be the same or different. The pump beam has a wavelength shorter than the signal wavelengths. Pump sources **20** and **52** collectively produce a pump beam of wavelength λ_p. An amplified signal is then output through signal output port **24**. Pump sources **20** and **52** are coupled in through WDM couplers **34** and **58** which transmit signal wavelength λ_s but couple over the pump wavelength λ_p. First lossy member **28** is positioned between pump input port **26** and signal output port **24**. In this embodiment, the signal flows in a first direction and the pump beam flows in a reverse direction relative to the first direction. First and second lengths of amplifier fiber **14** and **16** are pumped in a counter-propagating manner. It may also be desirous to have bi-directional pumping in second length of amplifier fiber **16** to increase the power amplifier gain without severely impacting the noise figure of multi-stage optical amplifier **10**. Other elements, including but not limited dispersion compensating element **33**, gain equalization element and add/drop multiplexer **31** may be included and positioned between first and second lengths of amplifier fiber **14** and **16**.

In another embodiment, illustrated in FIGS. **8**(*b*)–**8**(*c*), first length of amplifier fiber **14** is a distributed Raman amplifier fiber and second length of amplifier fiber **16** is a discrete Raman amplifier fiber. A distributed Raman amplifier fiber is an amplifier where at least some part of the transmission link is pumped and involved in amplification. In this embodiment, first lossy member **28** is not positioned between first and second lengths of amplifier fiber **14** and **16**. In FIG. **8**(*b*) distributed amplification is added with only counter-propagating Raman pumps. When access at a mid-point stage exists alternate band pumps are added at different spatial points to minimize nonlinear interaction between pumps. In FIG. **8**(*c*) mid-span access is not available but bi-directional pumping is allowed. The embodiment of FIG. **8**(*c*) can be used where alternate band Raman pumps are launched in different directions in order to minimize interaction between pumps.

The open loop embodiment of multi-stage optical amplifier **10** can have three or more lengths of amplifier fiber. Referring now to FIG. **9**, an embodiment of multi-stage optical amplifier **10** is illustrated with third length of amplifier fiber **42** coupled to a third pump source **60** which is turn is coupled to a third pump input port **62**. WDM coupler **64** is coupled to third pump input port **62**. Some or all of first, second and third pump sources **20, 52** and **60** can be laser diode sources. Pump source **60** produces a pump beam of wavelength λ_{p3}. Wavelengths λ_{p1}, λ_{p2} and λ_{p3} can be the same or different. Pump sources **20, 44** and **60** collectively produce pump beam of wavelength λ_p. An amplified signal is then output through signal output port **24**.

As illustrated in FIGS. **10** and **11** each of pump source **20, 52** and **60** can include multiple pump sources whose outputs can be combined using wavelength and polarization multiplexing. Multiple combination gratings **66** and PBS's **68** can be utilized. Additionally, some or all of the multiple pump sources which comprise pump sources **20, 52** and **60** can be laser diodes.

Referring now to FIG. **12**, a spectrum broadening device **70** can be coupled to each pump source **20, 52** and **60**. This is particularly useful for laser diode pump sources. Spectrum broadening device **70** broadens the spectrum while minimizing Brillouin threshold. Suitable spectrum broadening devices **70** include but are not limited to, (i)a grating that is sufficiently broadband that can be chirped and cascade individual wavelengths, (ii) positioning a grating in a laser diode external cavity to cause appropriate line broadening and (iii) a dithering drive. Additionally pump pulsing can be used to broaden the spectrum.

The Brillouin threshold is reached when the following condition is satisfied:

$$\tilde{g}_B=P_0^{LD}\cdot L_{eff}/A_{eff}\leqq 18$$

where

P_0^{LD}=power of laser diode

L_{eff}=$1/\alpha\cdot[1-\exp^{-\alpha L}]$effective pumping length

A_{eff}=effective area of fiber **12**

$\tilde{g}_B=\Delta\gamma_B/\Delta\gamma_B+\Delta\gamma_P\cdot g_B$

$\tilde{g}_B=\Delta\gamma_B/\Delta\gamma_B+\Delta\gamma_P\cdot g_B$

Multi-stage optical amplifier **10** can be an in-line broadband amplifier, a booster amplifier, a broadband pre-amplifier and incorporated in any variety of different broadband communication systems. In another embodiment, illustrated in FIG. **13**, the present invention is a broadband booster amplifier **72** that includes a multi-stage optical amplifier **10** coupled to a transmitter **73**. Transmitter **73** can include a WDM combiner **74** and a plurality of transmitters **76**. The plurality of transmitters **76** transmit a plurality of wavelengths. The plurality of wavelengths may include at least a first band of wavelengths and a second band of wavelengths. With the present invention, a variety of different transmitters **76** can be utilized including but not limited to laser diodes, tunable lasers, or broadband sources such as continuum sources or light-emitting diodes.

FIG. **14** illustrates a broadband pre-amplifier embodiment of the present invention. Broadband pre-amplifier **78** includes multi-stage optical amplifier **10** coupled to a receiver **80**. Receiver **80** can include a WDM splitter **82** coupled to a plurality of receivers **84**. Suitable receivers **84** include but are not limited to germanium or InGaAs or InGaAsP detectors followed by electronics well known to those skilled in the art.

In another embodiment, illustrated in FIG. **15**, the present invention is a broadband communication system **86**. In this embodiment, multi-stage optical amplifier **10** is an in-line broadband amplifier. Multi-stage optical amplifier **10** is coupled to one or more transmitters **73** and one or more receivers **80**.

FIG. **16** illustrates another embodiment of the present invention which is a broadband communication system **88** that includes multi-stage optical amplifier **10** coupled to a broadband pre-amplifier **90**. Multi-stage optical amplifier **10** is coupled to one or more transmitters **73** and broadband pre-amplifier **90** is coupled to one or more receivers **80**.

FIG. **17** illustrates yet another embodiment of a broadband communication system **92** with a broadband booster amplifier **94** coupled to multi-stage optical amplifier **10**. One or more transmitters **73** is coupled to broadband booster amplifier **94**. One or more receivers **80** is coupled to multi-stage optical amplifier **10**.

Another embodiment of a broadband communication system **96** is illustrated in FIG. **18**. In this embodiment, an in-line amplifier **98** is coupled to receiver **80** and to a transmitter **100**. Transmitter includes multi-stage optical amplifier **10** coupled to transmitter **73**.

FIG. **19** illustrates another broadband communication system **102** of the present invention. Broadband communication system **102** includes multi-stage optical amplifier **10** coupled to broadband booster amplifier **94** and broadband pre-amplifier **90**. Broadband booster amplifier **94** is coupled to one or more transmitters **73**. Broadband pre-amplifier **90** is coupled to one or more receivers **80**.

While embodiments of the invention have been illustrated and described, it is not intended that these embodiments illustrate and describe all possible forms of the invention. Rather, the words used in the specification are words of description rather than limitation, and it is understood that various changes may be made without departing from the spirit and scope of the invention.

What is claimed is:

1. A multi-stage optical amplifier, comprising:

one or more optical fibers including at least a distributed Raman amplifier fiber and a discrete Raman amplifier fiber, the one or more optical fibers configured to communicate with one or more signal sources producing a plurality of signal wavelengths λ_s and at least two pump sources that produce one or more pump beam wavelengths λ_p, the distributed Raman amplifier fiber is configured to introduce an effective optical noise figure to at least a portion of the plurality of signal wavelengths λ_s of less than 8 dB and less than an effective optical noise figure introduced by the discrete Raman amplifier fiber, wherein at least one of the one or more pump beam wavelengths λ_p is shorter than at least a portion of the plurality of signal wavelengths λ_s, and wherein the discrete Raman amplifier fiber is capable of introducing a gain level to at least some of the plurality of wavelengths λ_s of at least 5 dB;

a signal input port coupled to the one or more optical fibers;

a signal output port coupled to the one or more optical fibers;

a first pump input port, the distributed Raman amplifier fiber being positioned between the signal input port and the first pump input port and the discrete Raman amplifier fiber being positioned between the first pump input port and signal output port;

a second pump input port coupled to the one or more optical fibers and positioned between the first pump input port and the signal output port; and

wherein the plurality of signal wavelengths λ_s flow in a first direction and the one or more pump beam wavelengths λ_p flow in a direction counter to the first direction, and wherein at least one of the distributed Raman amplifier and the discrete Raman amplifier comprises a dispersion compensating fiber.

2. The multi-stage optical amplifier of claim **1**, wherein the first pump input port is coupled to a first pump source, and the second pump input port is coupled to a second pump source.

3. The multi-stage optical amplifier of claim **2**, wherein the first pump source produces a pump beam comprising one or more wavelengths λ_{p1} and the second pump source produces a pump beam comprising one or more wavelengths λ_{p2}.

4. The multi-stage optical amplifier of claim **3**, wherein the one or more wavelengths λ_{p1} and the one or more wavelengths λ_{p2} are the same.

5. The multi-stage optical amplifier of claim **3**, wherein at least a portion of the one or more wavelengths λ_{p1} and the one or more wavelengths λ_{p2} are different.

6. The multi-stage optical amplifier of claim **1**, wherein the distributed and discrete Raman amplifier fibers have lengths greater than or equal to 200 meters.

7. The multi-stage optical amplifier of claim **1**, wherein the one or more pump beam wavelengths λ_p are in the range of 1300 nm to 1530 nm.

8. The multi-stage optical amplifier of claim **1**, wherein at least a portion of the plurality of signal wavelengths λ_s is in the range of 1430 to 1530 nm.

9. The multi-stage optical amplifier of claim **1**, further comprising:

at least one WDM coupler to couple a pump path from the signal input port to the signal output port.

10. The multi-stage optical amplifier of claim **1**, wherein the one or more optical fibers includes a third Raman amplifier fiber.

11. The multi-stage optical amplifier of claim **10**, further comprising:

a third pump source coupled to the third Raman amplifier fiber.

12. The multi-stage optical amplifier of claim **11**, wherein the one or more optical fibers includes a fourth Raman amplifier fiber.

13. The multi-stage optical amplifier of claim **2**, wherein each of the first and second pump sources comprises a laser diode pump source.

14. The multi-stage optical amplifier of claim **2**, further comprising:

at least a first lossy member positioned between the first pump input port and the signal output port, the at least first lossy member being lossy in at least one direction.

15. The multi-stage optical amplifier of claim **14**, wherein the at least a first lossy member includes an optical isolator.

16. The multi-stage optical amplifier of claim **14**, wherein the at least a first lossy member includes an add/drop multiplexer.

17. The multi-stage optical amplifier of claim **14**, wherein the at least a first lossy member includes a gain equalization member.

18. The multi-stage optical amplifier of claim **14**, wherein the at least a first lossy member includes a dispersion compensation element.

19. The multi-stage optical amplifier of claim **14**, wherein the at least a first lossy member includes a WDM coupler.

20. A multi-stage optical amplifier, comprising:

one or more optical fibers including at least a distributed Raman amplifier fiber and a discrete Raman amplifier fiber, the one or more optical fibers configured to communicate with one or more signal sources producing a plurality of signal wavelengths λ_s and at least two pump sources that produce one or more pump beam wavelengths λ_p, wherein at least one of the one or more pump beam wavelengths λ_p is shorter than at least a portion of the plurality of signal wavelengths λ_s, and wherein at least one of the distributed Raman amplifier fiber and the discrete Raman amplifier fiber comprises an optical fiber cut-off wavelength that is shorter than at least one of the one or more pump beam wavelengths λ_p;

a signal output port coupled to the one or more optical fibers;

a first pump input port, the distributed Raman amplifier fiber being positioned between the signal input port and the first pump input port and the discrete Raman amplifier fiber being positioned between the first pump input port and signal output port; and

a second pump input port coupled to the one or more optical fibers and positioned between the first pump input port and the signal output port.

21. The multi-stage optical amplifier of claim **20**, wherein the optical fiber cut-off wavelength of the distributed Raman amplifier fiber is shorter than the one or more pump beam wavelengths λ_p.

22. The multi-stage optical amplifier of claim **20**, wherein the optical fiber cut-off wavelength of the discrete Raman amplifier fiber is shorter than the one or more pump beam wavelengths λ_p.

23. The multi-stage optical amplifier of claim **20**, wherein the first pump input port is coupled to a first pump source, and the second pump input port is coupled to a second pump source.

24. The multi-stage optical amplifier of claim **20**, wherein the first pump source produces a pump beam comprising one or more wavelengths λ_{p1}, and the second pump source produces a pump beam comprising one or more wavelengths λ_{p2}.

25. The multi-stage optical amplifier of claim **24**, wherein the one or more wavelengths λ_{p1} and the one or more wavelengths λ_{p2} are the same.

26. The multi-stage optical amplifier of claim 24, wherein at least a portion of the one or more wavelengths λ_{p1} and the one or more wavelengths λ_{p2} are different.

27. The multi-stage optical amplifier of claim 20, wherein the distributed and discrete Raman amplifier fibers have lengths greater than or equal to 200 meters.

28. The multi-stage optical amplifier of claim 20, wherein the one or more pump beam wavelengths λ_p are in the range of 1300 nm to 1530 nm.

29. The multi-stage optical amplifier of claim 20, wherein at least a portion of the plurality of signal wavelengths λ_s is in the range of 1430 to 1530 nm.

30. The multi-stage optical amplifier of claim 20, wherein an effective optical noise figure of the distributed Raman amplifier fiber is less than an optical noise figure of the discrete Raman amplifier fiber for at least a portion of the plurality of signal wavelengths.

31. The multi-stage optical amplifier of claim 20, wherein the discrete Raman amplifier fiber provides to at least some of the signal wavelengths λ_s a higher gain than the distributed Raman amplifier fiber.

32. The multi-stage optical amplifier of claim 20, further comprising:

at least one WDM coupler to couple a pump path from the signal input port to the signal output port.

33. The multi-stage optical amplifier of claim 20, wherein at least one of the distributed and discrete Raman amplifier fibers comprises a dispersion compensating fiber.

34. The multi-stage optical amplifier of claim 20, wherein the distributed Raman amplifier fiber has an effective optical noise figure of less than 8 dB over the wavelengths λ_s.

35. The multi-stage optical amplifier of claim 20, wherein the discrete Raman amplifier fiber provides a gain level of at least 5 dB to at least some of the signal wavelengths λ_s.

36. The multi-stage optical amplifier of claim 20, wherein the one or more optical fibers includes a third Raman amplifier fiber.

37. The multi-stage optical amplifier of claim 36, further comprising:

a third pump source coupled to the third Raman amplifier fiber.

38. The multi-stage optical amplifier of claim 37, wherein the one or more optical fibers includes a fourth Ram an amplifier fiber.

39. The multi-stage optical amplifier of claim 20, wherein each of the first and second pump sources comprises a laser diode pump source.

40. The multi-stage optical amplifier of claim 20, further comprising:

at least a first lossy member positioned between the first pump input port and the signal output port, the at least first lossy member being lossy in at least one direction.

41. The multi-stage optical amplifier of claim 40, wherein the at least first lossy member includes an optical isolator.

42. The multi-stage optical amplifier of claim 40, wherein the at least first lossy member includes an add/drop multiplexer.

43. The multi-stage optical amplifier of claim 40, wherein the at least first lossy member includes a gain equalization member.

44. The multi-stage optical amplifier of claim 40, wherein the at least first lossy member includes a dispersion compensation element.

45. The multi-stage optical amplifier of claim 40, wherein the at least first lossy member includes a WDM coupler.

46. The multi-stage optical amplifier of claim 20, wherein the plurality of signal wavelengths λ_s flow in a first direction and the one or more pump beam wavelengths λ_p flow in a direction counter to the first direction.

47. A multi-stage optical amplifier, comprising:

one or more optical fibers including at least a distributed Raman amplifier fiber and a discrete Raman amplifier fiber, at least a portion of one of the distributed Raman amplifier fiber and the discrete Raman amplifier fiber comprising a dispersion compensating fiber, the one or more optical fibers configured to communicate with one or more signal sources producing a plurality of signal wavelengths λ_s and at least two pump sources that produce one or more pump beam wavelengths λ_p;

a signal input port coupled to the one or more optical fibers;

a first pump input port, the distributed Raman amplifier fiber being positioned between the signal input port and the first pump input port and the discrete Raman amplifier fiber being positioned between the first pump input port and signal output port; and

a second pump input port coupled to the one or more optical fibers and positioned between the first pump input port and the signal output port.

48. The multi-stage optical amplifier of claim 47, wherein the dispersion compensating fiber has a zero dispersion point that is shifted to wavelengths greater than 1500 nm using a waveguide dispersion property.

49. The multi-stage optical amplifier of claim 47, wherein the plurality of signal wavelengths λ_s flow in a first direction and the one or more pump beam wavelengths λ_p flow in a direction counter to the first direction.

50. The multi-stage optical amplifier of claim 47, wherein the first pump input port is coupled to a first pump source, and the second pump input port is coupled to a second pump source.

51. The multi-stage optical amplifier of claim 47, further comprising:

at least a first lossy member positioned between the first pump input port and the signal output port, the at least first lossy member being lossy in at least one direction.

52. The multi-stage optical amplifier of claim 47, wherein the distributed and discrete Raman amplifier fibers have lengths greater than or equal to 200 meters.

53. A multi-stage optical amplifier, comprising:

one or more optical fibers including at least a distributed Raman amplifier fiber and a discrete Raman amplifier fiber, the one or more optical fibers configured to receive a plurality of signal wavelengths λ_s;

a signal input port coupled to the one or more optical fibers;

a first pump input port, the distributed Raman amplifier fiber being positioned between the signal input port and the first pump input port and the discrete Raman amplifier fiber being positioned between the first pump input port and signal output port;

a second pump input port coupled to the one or more optical fibers and positioned between the first pump input port and the signal output port; and

at least a first pump source coupled to one of the first and second pump input ports, the at least a first pump source including a plurality of pump sources comprising outputs that are combined using wavelength multiplexing and using, for at least one pump wavelength, polarization multiplexing.

54. The multi-stage optical amplifier of claim 53, wherein the plurality of pump sources include multiple gratings.

55. The multi-stage optical amplifier of claim 53, wherein at least a portion of the plurality of pump sources comprise laser diodes.

56. The multi-stage optical amplifier of claim 53, wherein at least a portion of the plurality of pump sources comprise laser diodes each producing an output wavelength that is stabilized by at least one grating.

57. The multi-stage optical amplifier of claim 53, wherein the plurality of signal wavelengths λ_s flow in a first direction and the one or more pump beam wavelengths λ_p flow in a direction counter to the first direction.

58. The multi-stage optical amplifier of claim 53, further comprising:

at least a first lossy member positioned between the first pump input port and the signal output port, the at least first lossy member being lossy in at least one direction.

59. A multi-stage optical amplifier system, comprising:

a plurality of transmitters that produce a plurality of signal wavelengths λ_s;

a multi-stage optical amplifier comprising:

one or more optical fibers including at least a distributed Raman amplifier fiber and a discrete Raman amplifier fiber, the one or more optical fibers communicating with the plurality of transmitters and configured to be coupled to at least two pump sources that produce one or more pump beam wavelengths λ_p, the distributed Raman amplifier fiber is capable of introducing an effective optical noise figure to at least a portion of the plurality of signal wavelengths λ_s of less than 8 dB and less than an effective optical noise figure introduced by the discrete Raman amplifier fiber, wherein at least one of the one or more pump beam wavelengths λ_p is shorter than at least a portion of the plurality of signal wavelengths λ_s, wherein the discrete Raman amplifier fiber is capable of introducing a gain level to at least some of the plurality of wavelengths λ_s of at least 5 dB, and wherein at least one of the distributed Raman amplifier and the discrete Raman amplifier comprises a dispersion compensating fiber;

a signal input port coupled to the one or more optical fibers;

a signal output port coupled to the one or more optical fibers;

a first pump input port, the distributed Raman amplifier fiber being positioned between the signal input port and the first pump input port and the discrete Raman amplifier fiber being positioned between the first pump input port and signal output port;

a second pump input port coupled to the one or more optical fibers and positioned between the first pump input and the signal output port, wherein the plurality of signal wavelengths λ_s flow in a first direction and the one or more pump beam wavelengths λ_p flow in a direction counter to the first direction; and

a plurality of receivers coupled to the multi-stage optical amplifier.

60. A multi-stage optical amplifier system, comprising:

a plurality of transmitters that produce a plurality of signal wavelengths λ_s;

a multi-stage optical amplifier comprising:

one or more optical fibers including at least a distributed Raman amplifier fiber and a discrete Raman amplifier fiber, the one or more optical fibers communicating with the plurality of transmitters and configured to be coupled to at least two pump sources that produce one or more pump beam wavelengths λ_p, wherein the at least one of one or more pump beam wavelengths λ_p are shorter than at least a portion of the plurality of signal wavelengths λ_s, and wherein at least one of the distributed Raman amplifier fiber and the discrete Raman amplifier fiber comprises an optical fiber cut-off wavelength that is shorter than at least one of the one or more pump beam wavelengths λ_p;

a signal output port coupled to the one or more optical fibers;

a first pump input port, the distributed Raman amplifier fiber being positioned between the signal input port and the first pump input port and the discrete Raman amplifier fiber being positioned between the first pump input port and signal output port;

a second pump input port coupled to the one or more optical fibers and positioned between the first pump input port and the signal output port; and

a plurality of receivers coupled to the multi-stage optical amplifier.

61. The multi-stage optical amplifier system of claim 60, wherein the optical fiber cut-off wavelength of the distributed Raman amplifier fiber is shorter than the one or more pump beam wavelengths λ_p.

62. The multi-stage optical amplifier system of claim 60, wherein the optical fiber cut-off wavelength of the discrete Raman amplifier fiber is shorter than the one or more pump beam wavelengths λ_p.

63. A multi-stage optical amplifier system, comprising:

a plurality of transmitters that produce a plurality of signal wavelengths λ_s;

a multi-stage optical amplifier comprising:

one or more optical fibers including at least a distributed Raman amplifier fiber and a discrete Raman amplifier fiber, at least a portion of one of the distributed Raman amplifier fiber and the discrete Raman amplifier fiber comprises a dispersion compensating fiber, the one or more optical fibers facilitating communication with the plurality of transmitters and configured to be coupled to at least two pump sources that produce one or more pump beam wavelengths λ_p;

a signal input port coupled to the one or more optical fibers, a first pump input port, the distributed Raman amplifier fiber being positioned between the signal input port and the first pump input port and the discrete Raman amplifier fiber being positioned between the first pump input port and signal output port;

a second pump input port coupled to the one or more optical fibers and positioned between the first pump input port and the signal output port; and

a plurality of receivers coupled to the multi-stage optical amplifier.

64. The multi-stage optical amplifier system of claim 63, further comprising:

a transmission fiber coupled between the plurality of transmitters and the one or more optical fibers.

65. The multi-stage optical amplifier system of claim 64, wherein the dispersion compensating fiber has an approximately opposite sign of dispersion slope and an approximately opposite sign of dispersion relative to the transmission fiber.

66. A multi-stage optical amplifier system, comprising:

a plurality of transmitters that produce a plurality of signal wavelengths λ_s;

a multi-stage optical amplifier comprising:

one or more optical fibers facilitating communication with the plurality of transmitters and including at least a distributed Raman amplifier fiber and a discrete Raman amplifier fiber;

a signal input port coupled to the one or more optical fibers;

a first pump input port, the distributed Raman amplifier fiber being positioned between the signal input port and the first pump input port and the discrete Raman amplifier fiber being positioned between the first pump input port and signal output port;

a second pump input port coupled to the one or more optical fibers and positioned between the first pump input port and the signal output port;

at least a first pump source coupled to one of the first and second pump input ports, the at least a first pump source including a plurality of pump sources with outputs that are combined using wavelength multiplexing and using, for at least one pump wavelength, polarization multiplexing; and

a plurality of receivers coupled to the multi-stage optical amplifier.

67. The multi-stage optical amplifier of claim **1**, wherein the discrete Raman amplifier fiber is capable of introducing a gain level to at least a majority of the plurality of wavelengths λ_s of at least 5 dB.

68. The multi-stage optical amplifier of claim **47**, wherein the discrete Raman amplifier fiber is capable of introducing a gain level to at least a majority of the plurality of λ_s of at least 5 dB.

69. The multi-stage optical amplifier system of claim **63**, wherein the discrete Raman amplifier fiber is capable of introducing a gain level to at least a majority of the plurality of λ_s of at least 5 dB.

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